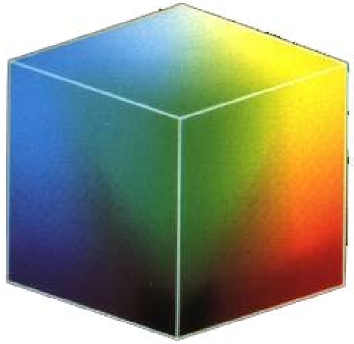
Einführung in Visual Computing

186.822



Color and Color Models

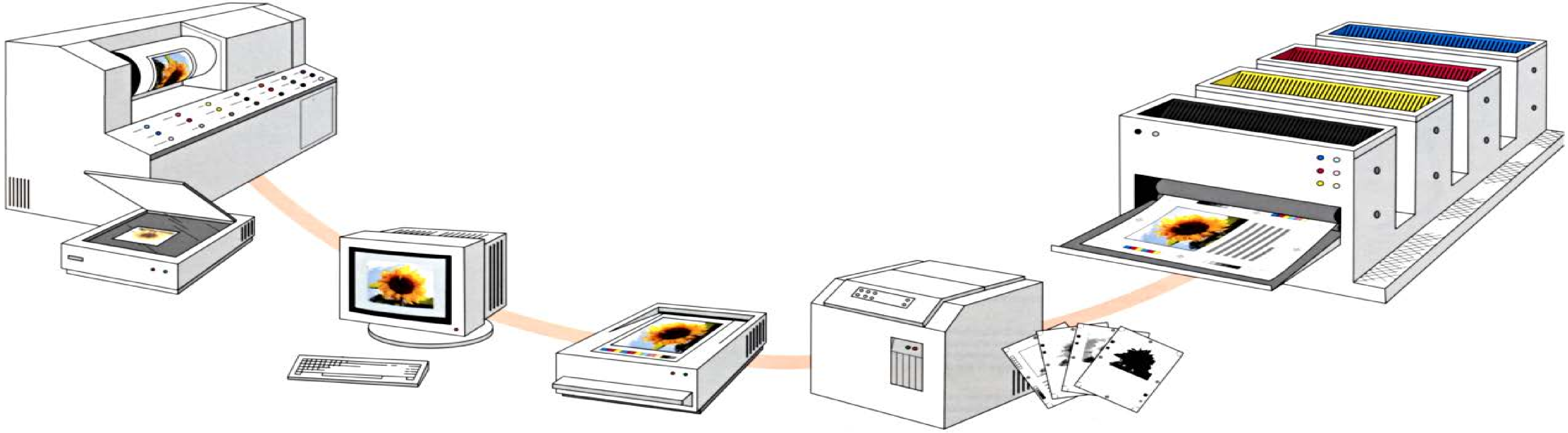
Werner Purgathofer

Color

- problem specification
- light and perception
- colorimetry
- device color systems
- color ordering systems
- color symbolism

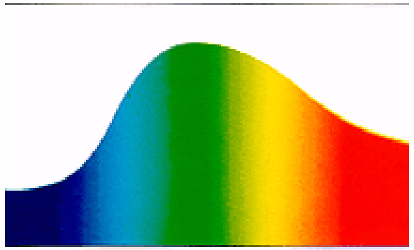
Color - Why Do We Care?

- Visual Computing is all about the generation and the manipulation of color images
- proper understanding & handling of color is necessary at every step



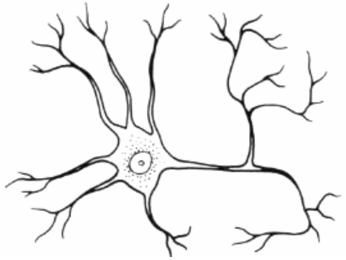
Color - A Visual Sensation

object

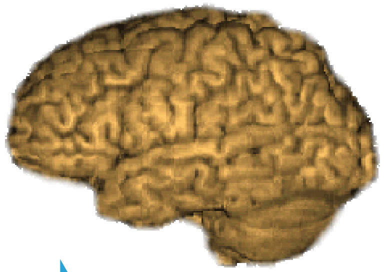


light stimulus

eye



nerve signal



brain

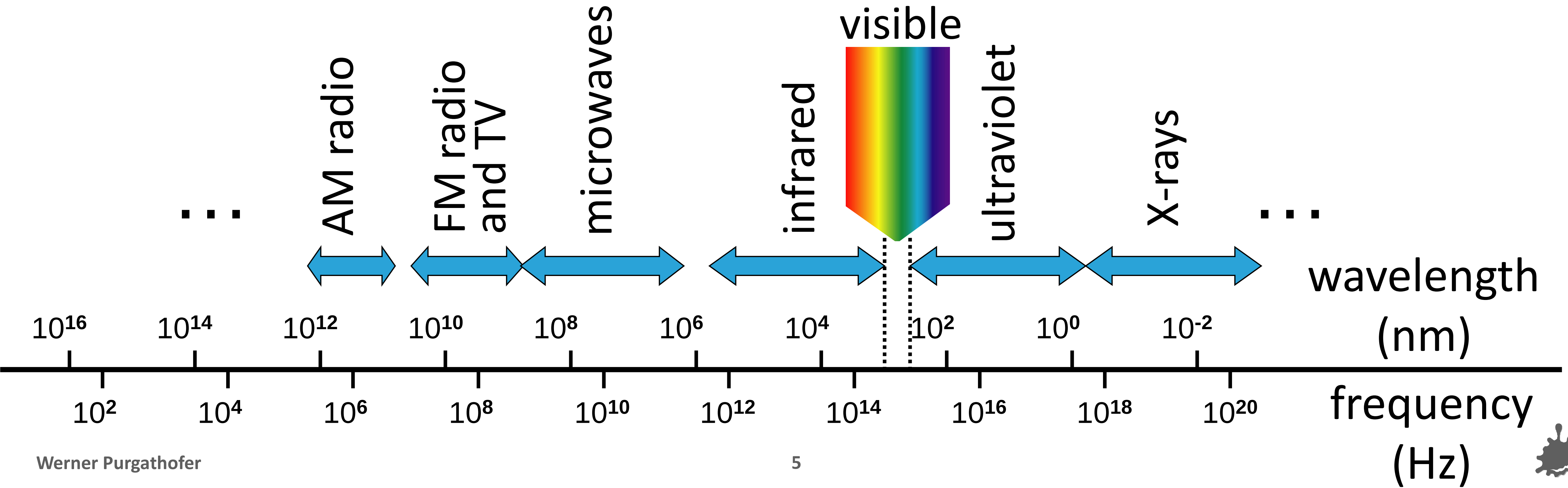
electromagnetic rays → color sensation

realm of direct observables

realm of psychology

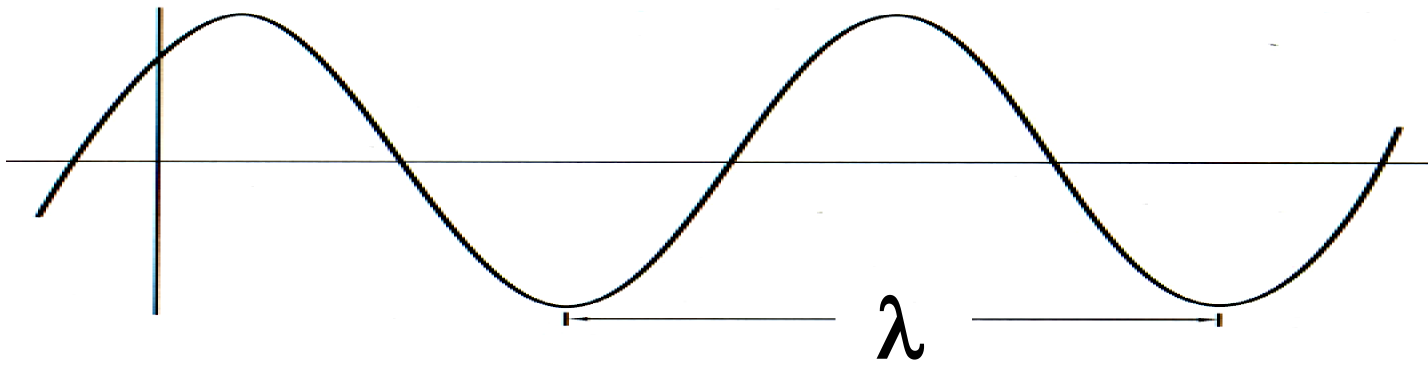
What is Light?

- "light" = narrow frequency band of electromagnetic spectrum
- red border: 380 THz ≈ 780 nm
- violet border: 780 THz ≈ 380 nm

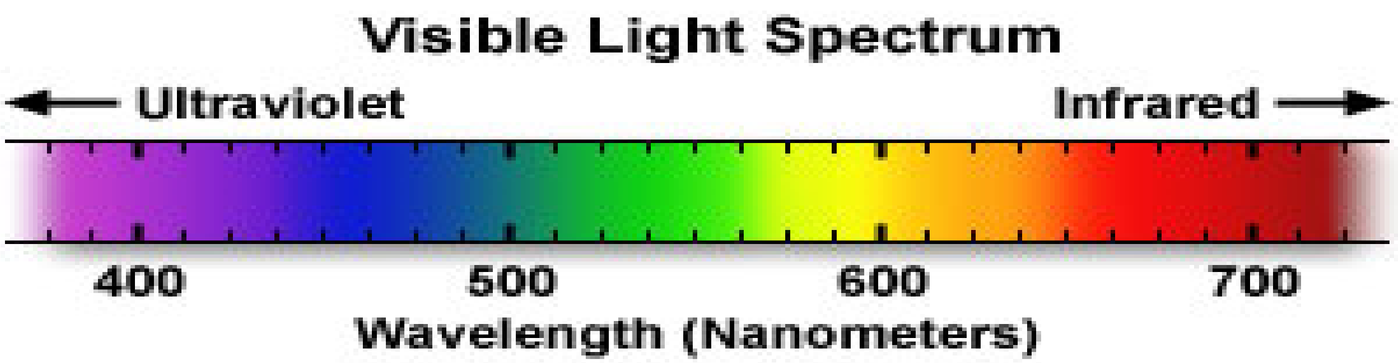


Light - An Electromagnetic Wave

- light is electromagnetic energy
- monochrome light can be described either by frequency f or wavelength λ
- $c = \lambda \cdot f$ (c = speed of light)



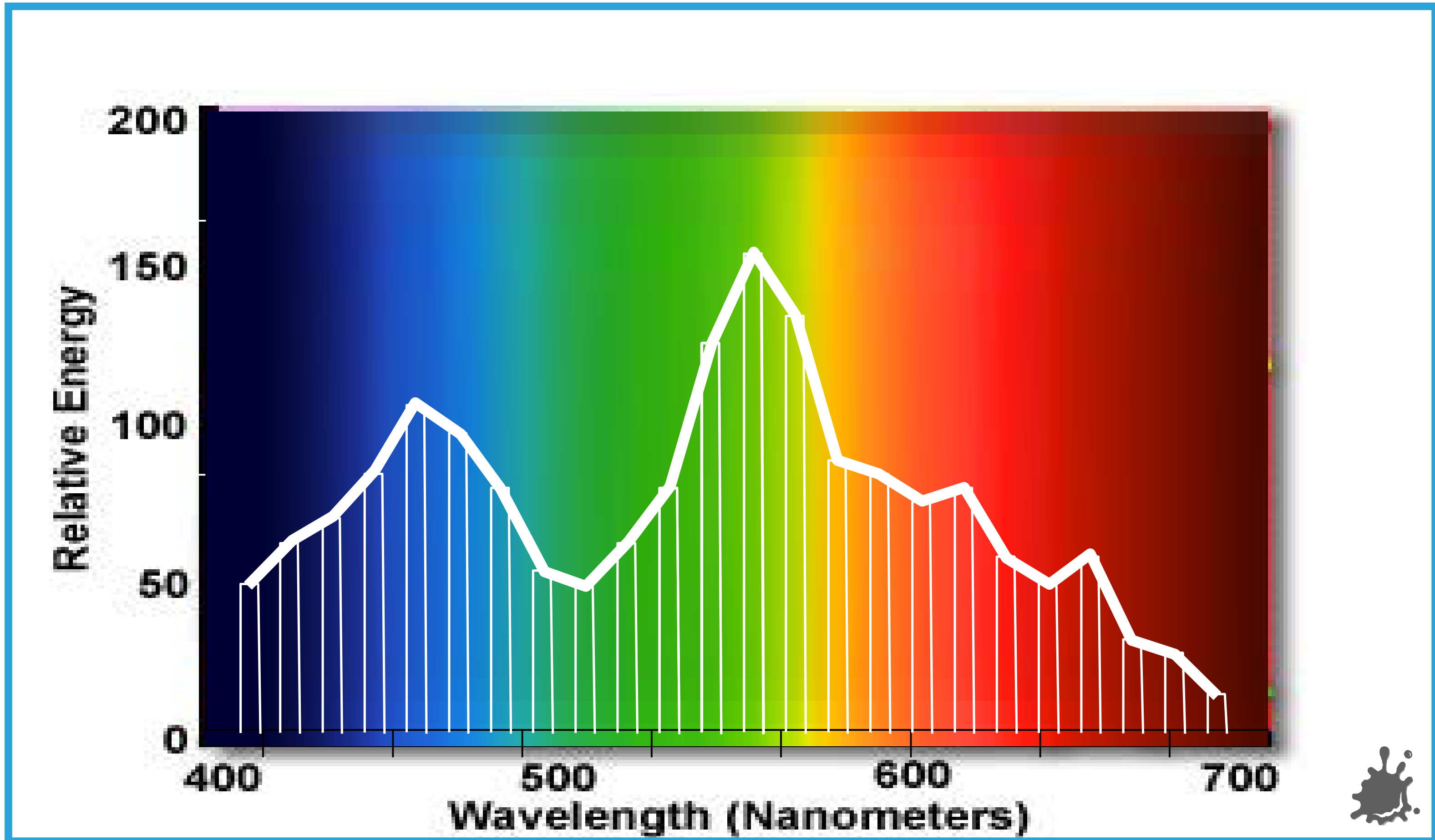
- shorter wavelength equals higher frequency



- red ≈ 700 nm
- violet ≈ 400 nm

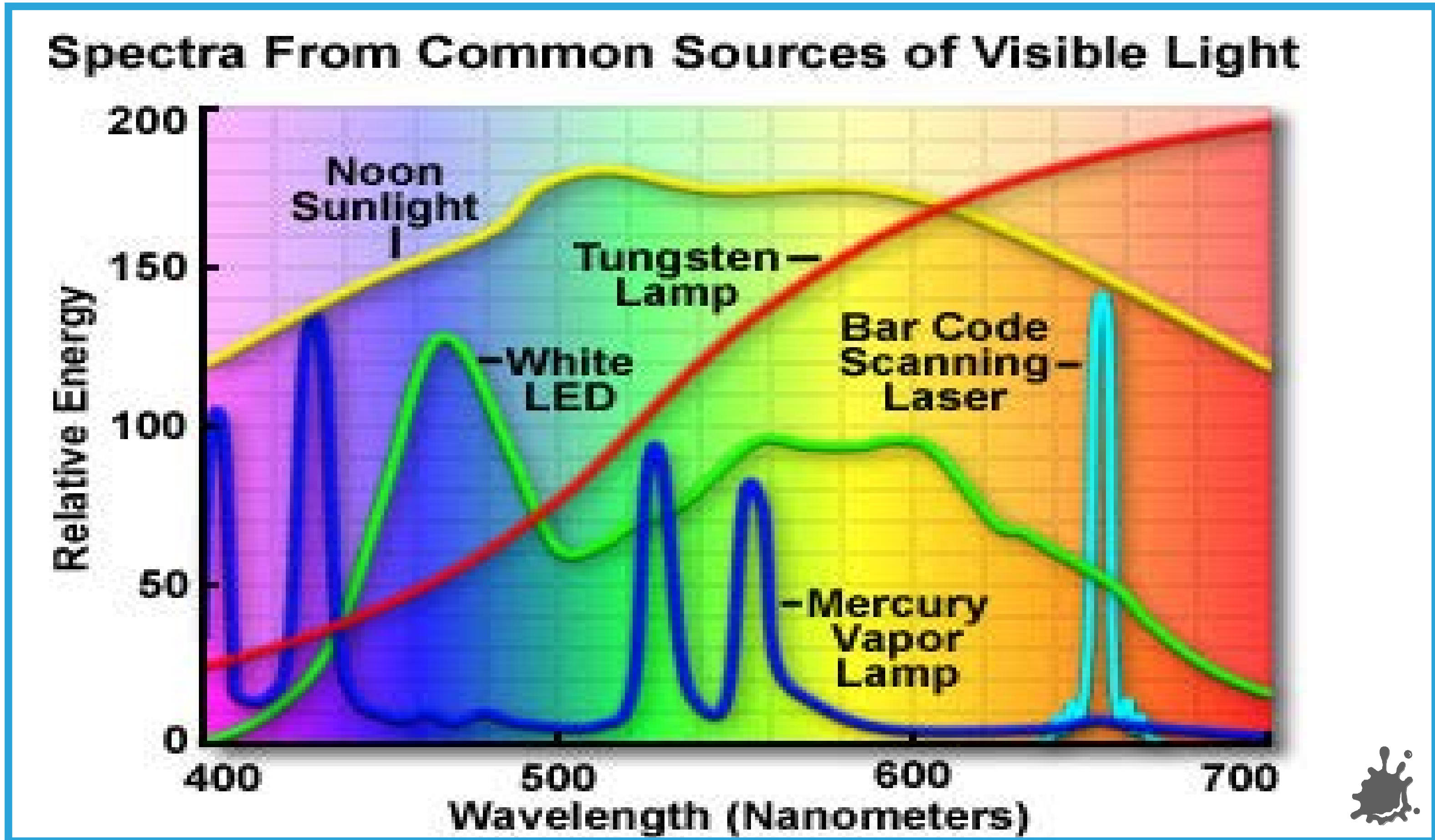
Light – Spectrum

- normally, a ray of light contains many different waves with individual frequencies
- the associated distribution of wavelength intensities per wavelength is referred to as the ***spectrum*** of a given ray or light source

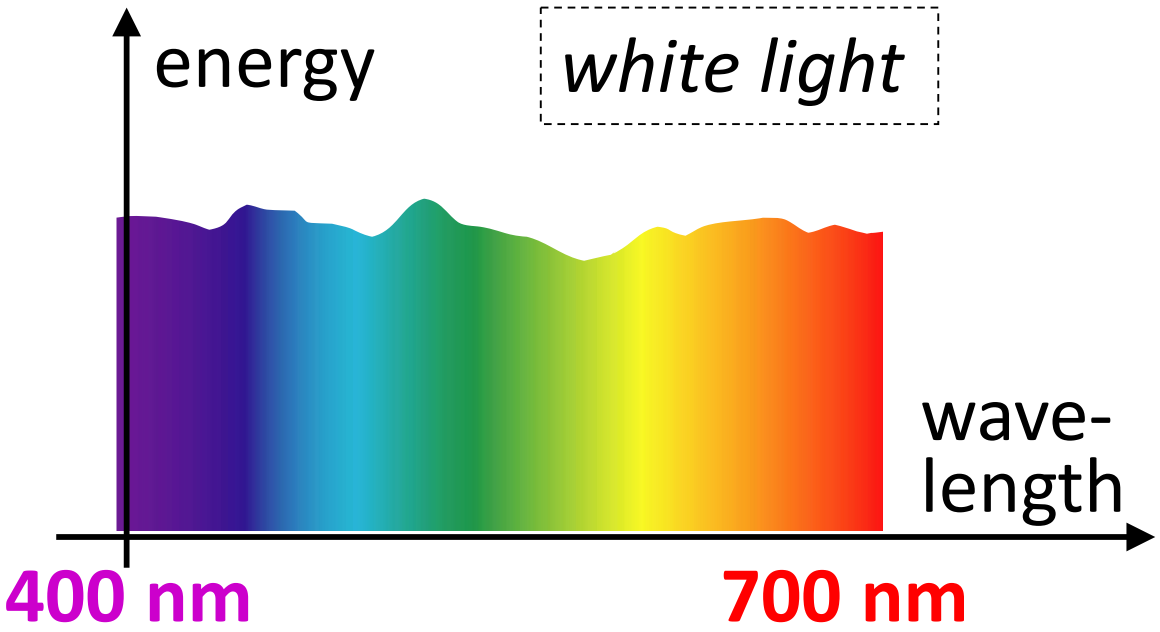


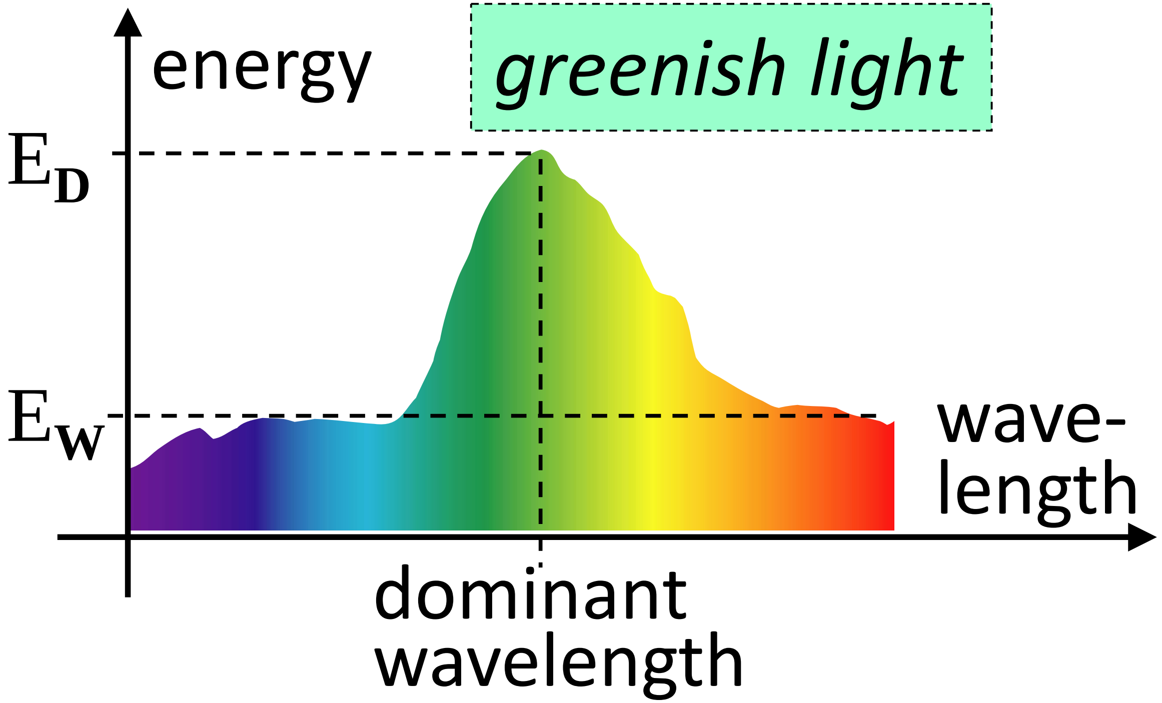
Light – Spectrum

- normally, a ray of light contains many different waves with individual frequencies
- the associated distribution of wavelength intensities per wave-length is referred to as the ***spectrum*** of a given ray or light source



Dominant Wavelength | Frequency





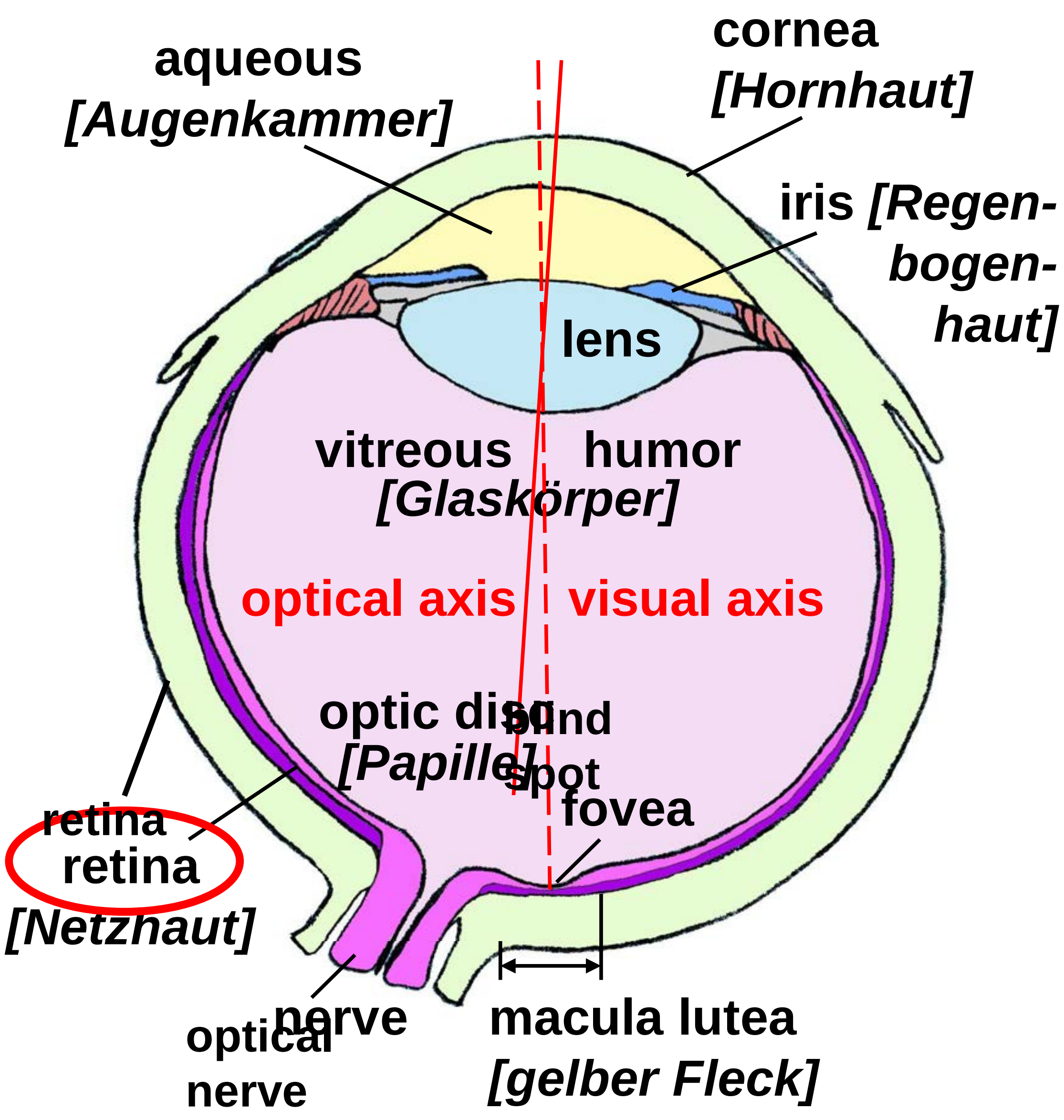
- dominant wavelength | frequency (hue, color)
- brightness (area under the curve)
- purity $\dfrac{E_D - E_W}{E_D}$

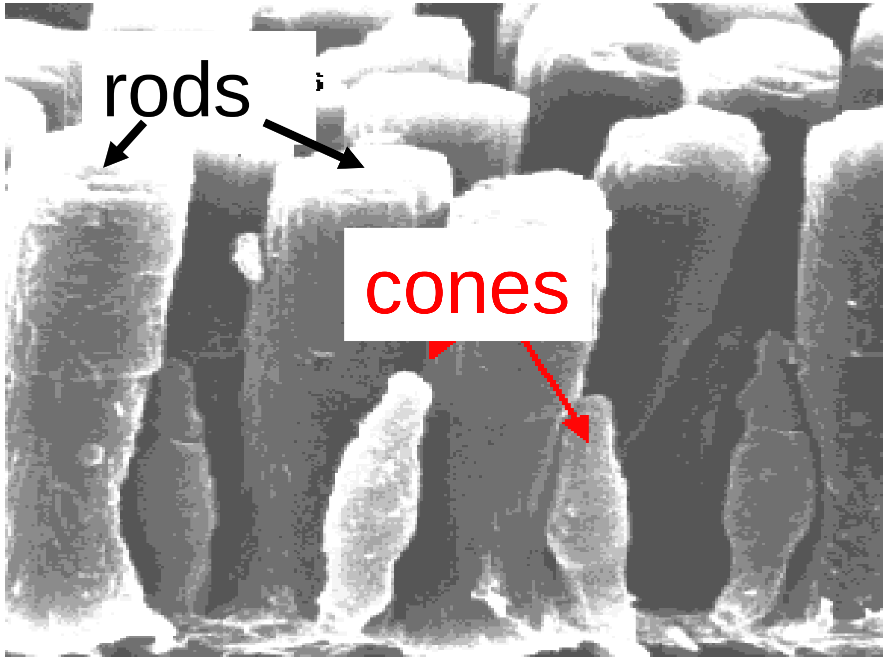
E_D ... dominant energy density

E_W ... white light energy density

The Human Eye

- retina contains
  - rods: b/w
  - cones: color

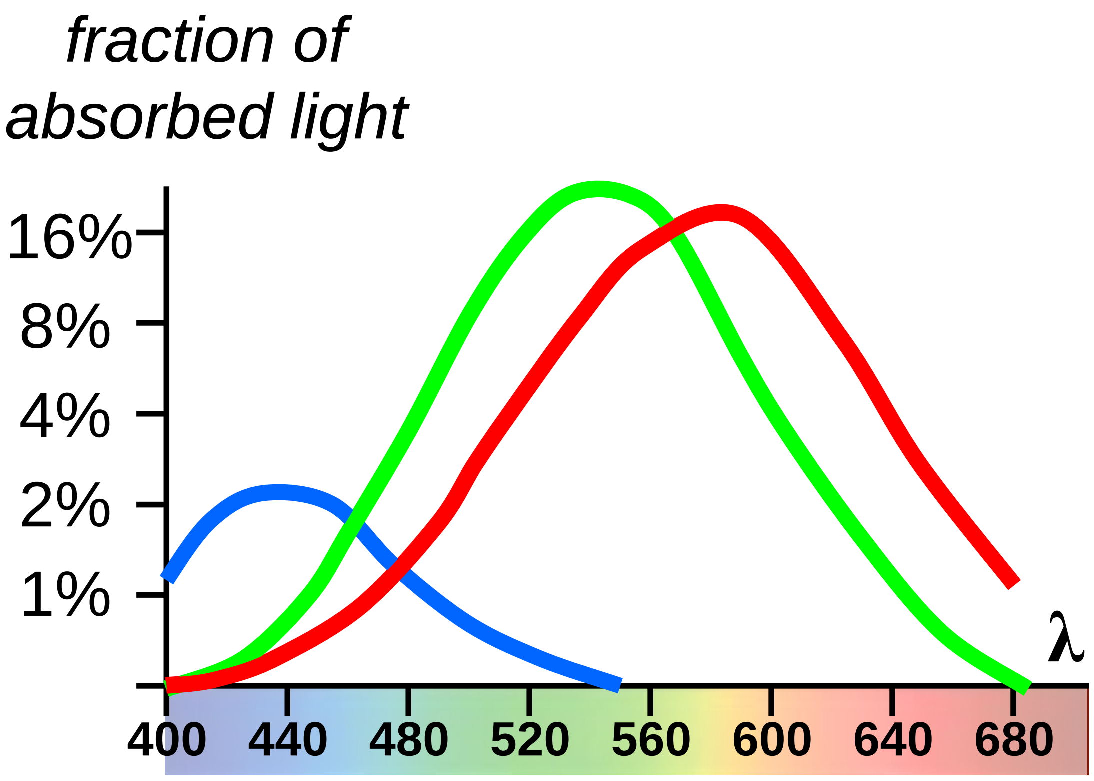




The Human Eye

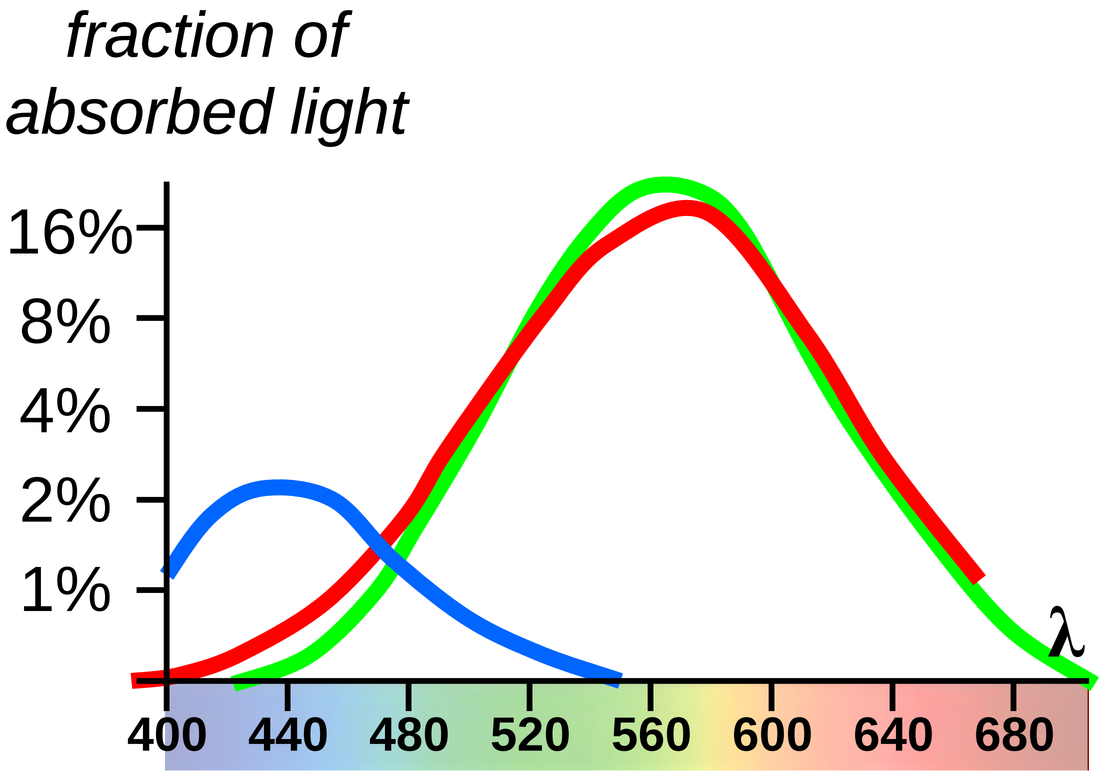
- 3 types of cones

- different wavelength sensitivities:
  - red
  - green
  - blue



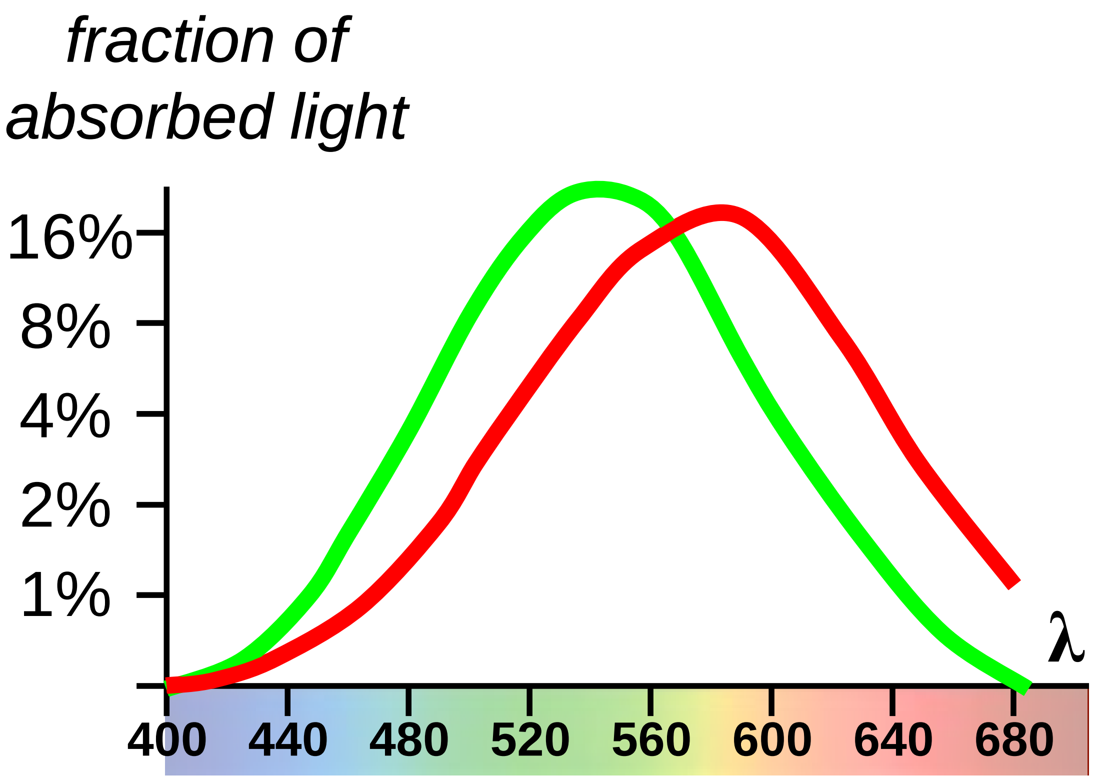
Color Blindness

- red/green blindness
  - red & green cones too similar



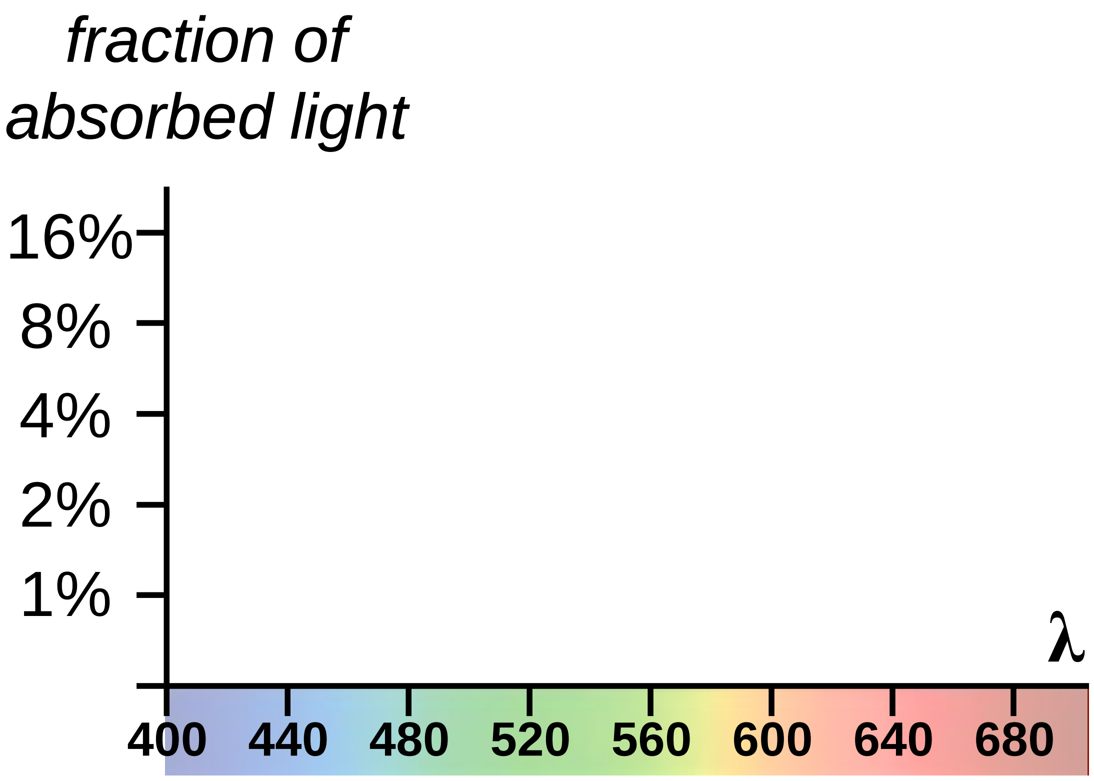
Color Blindness

- red/green blindness
  - red & green cones too similar
- blue blindness
  - no blue cones

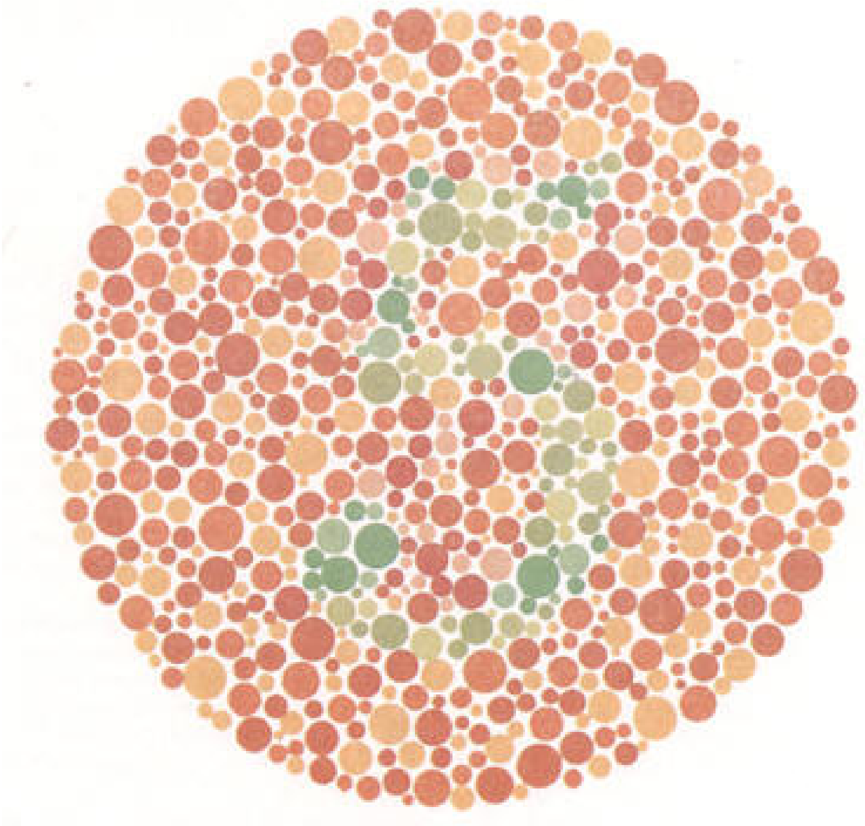


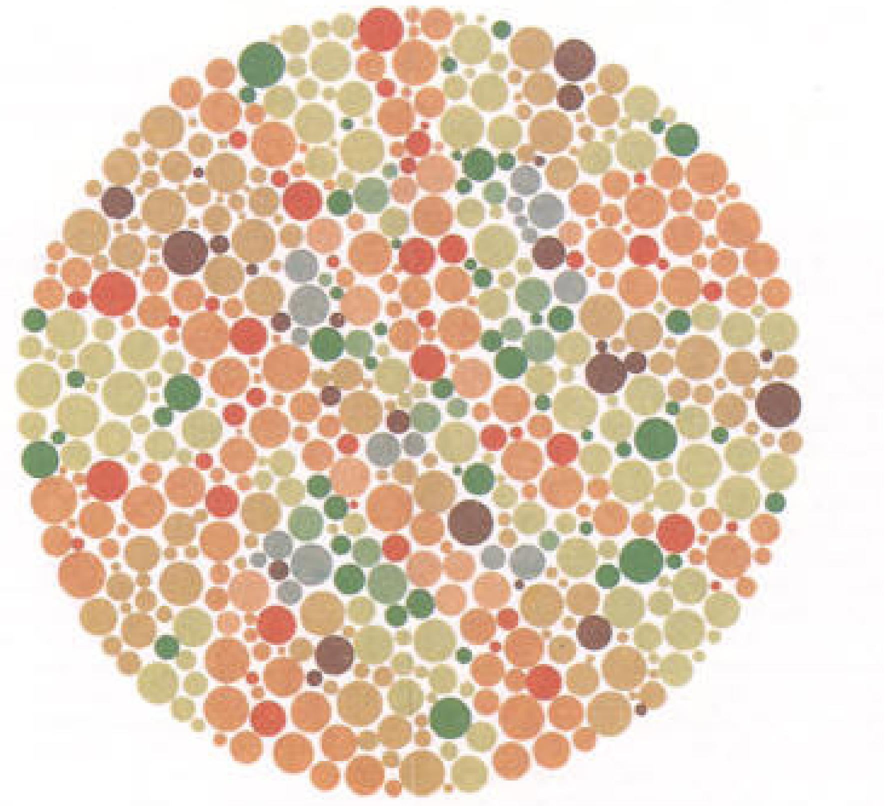
Color Blindness

- red/green blindness
  - red & green cones too similar
- blue blindness
  - no blue cones
- monochromatism
  - all cones missing



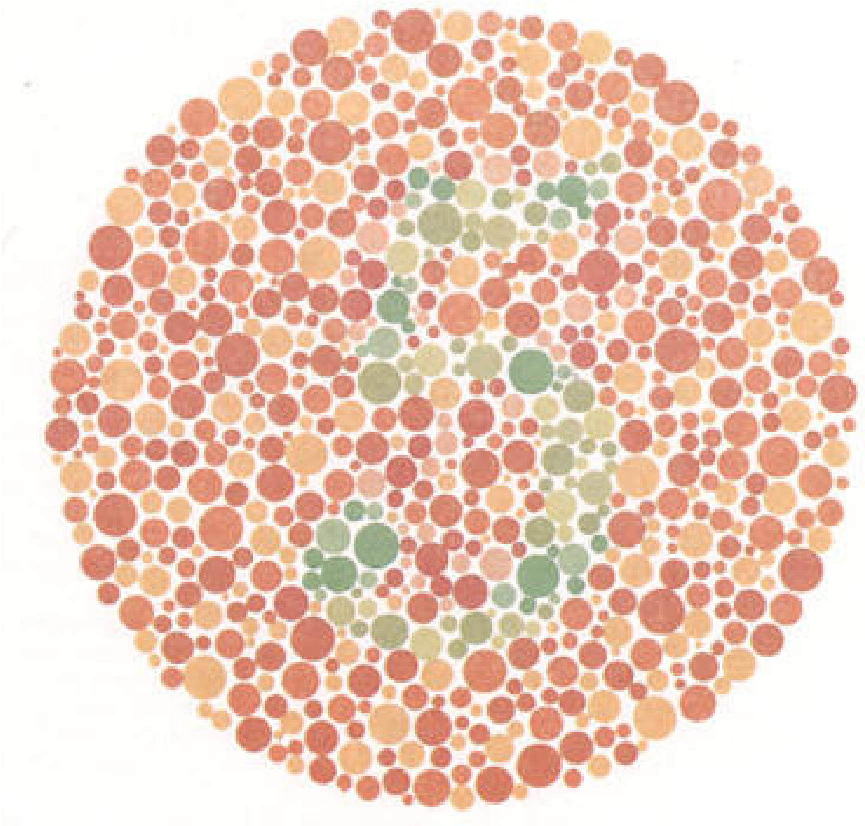
Color Blindness Tests



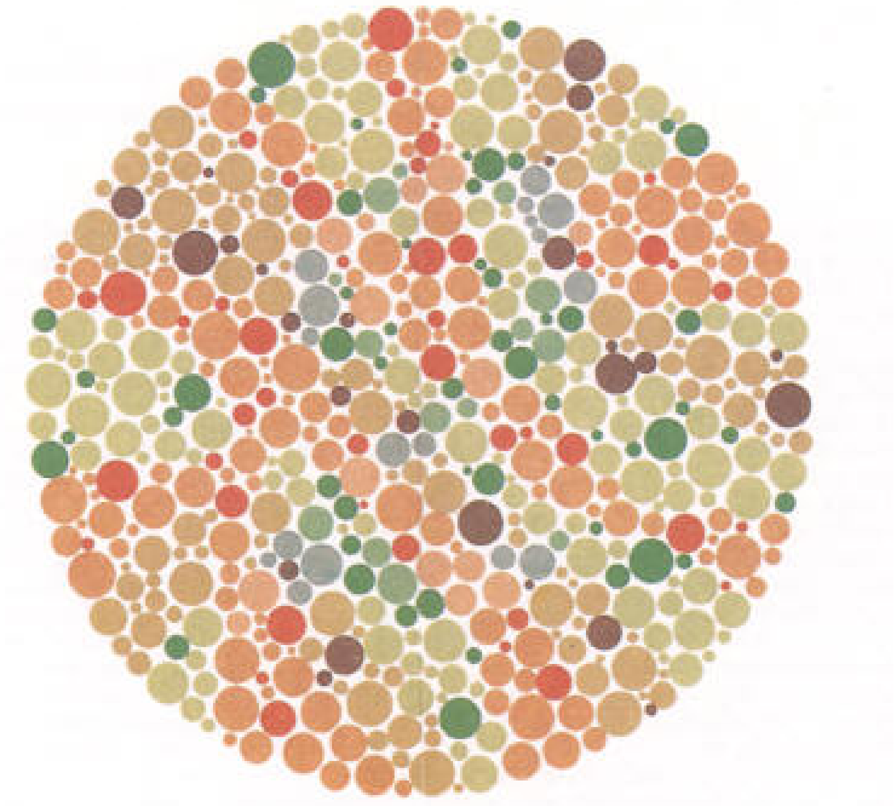


What do you see?

Color Blindness Tests

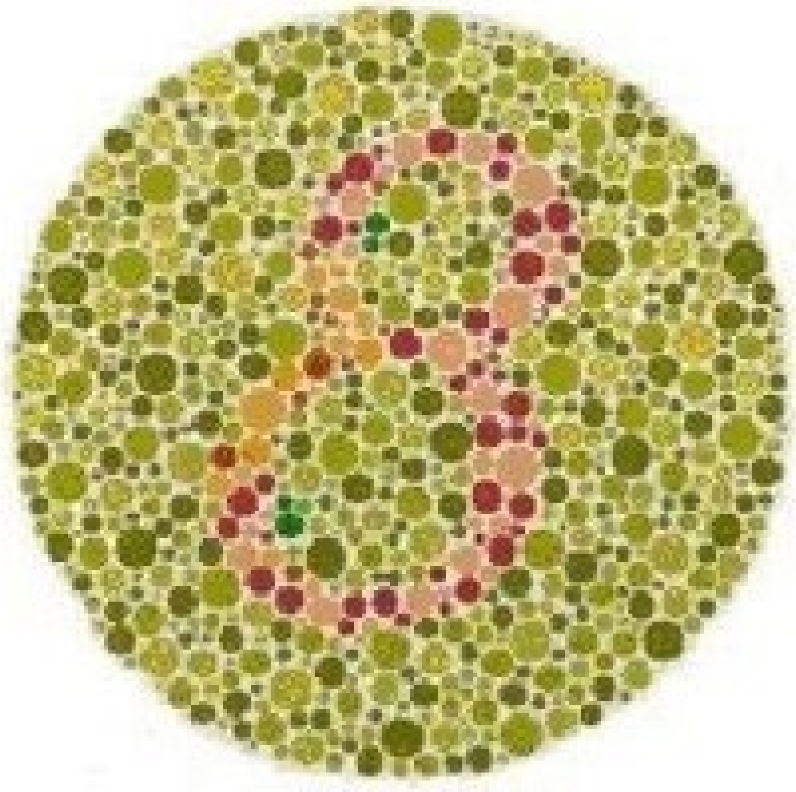


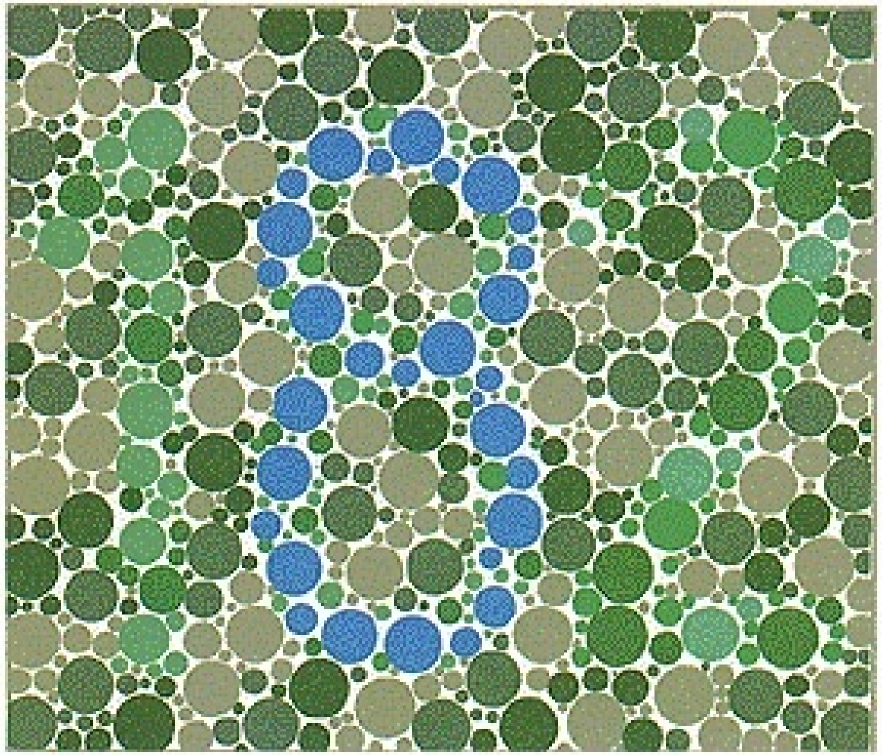
5 = normal
nothing = red/green blind



2 = red/green weak
nothing = normal

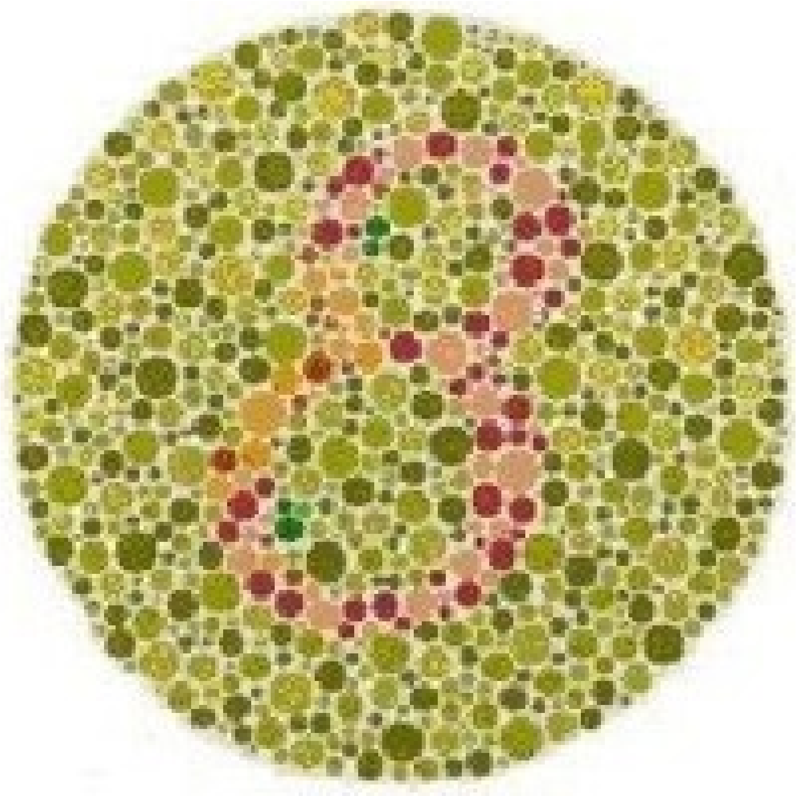
Color Blindness Tests

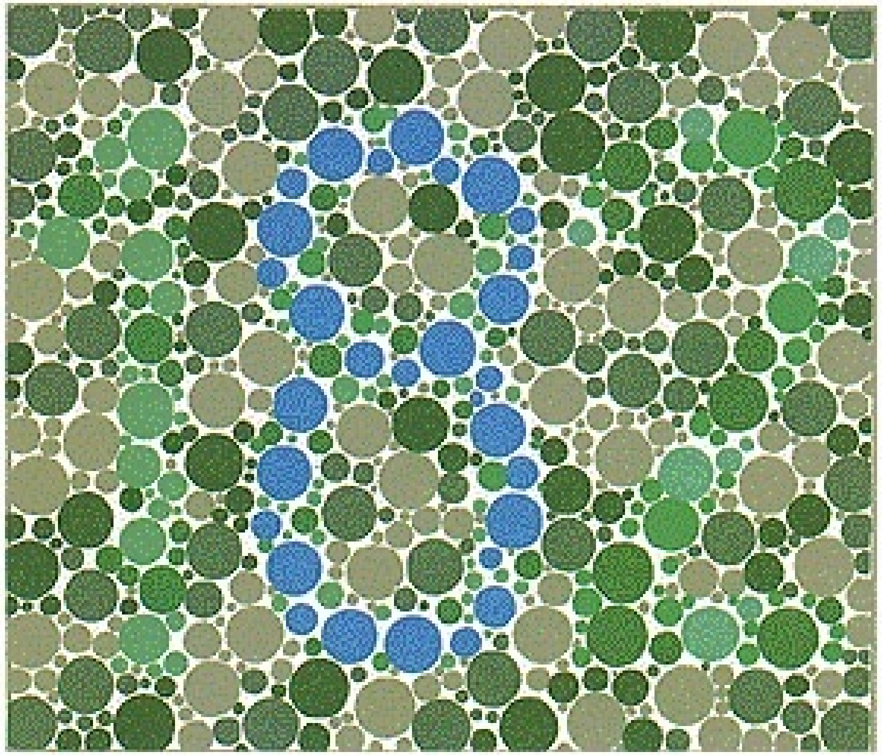




What do you see?

Color Blindness Tests





8 = normal
3 = red/green weak
nothing = red/green blind

8 = red/green blind
12 = blue/yellow blind
182 = normal

Color Blindness Example

normal vision

Color Blindness Example

red/green weakness

Color Blindness Example

red/green blindness

Color Spaces

- **Color Metric Spaces** (CIE XYZ, L*a*b*)
  - used to measure absolute values and differences – has roots in colorimetry
- **Device Color Spaces** (RGB, CMY, CMYK)
  - used in conjunction with devices
- **Color Ordering Spaces** (HSV, HLS)
  - used to find colors according to some criterion

- the distinction between them is somewhat obscured by the prevalence of multi-purpose RGB in computer graphics

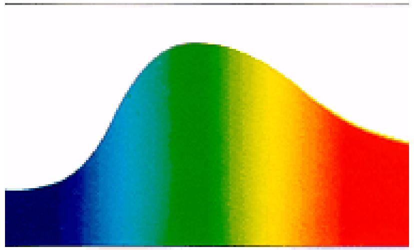
What is our Goal?

- to be able to ***quantify*** color in a meaningful, expressive, consistent and reproducible way

- problem: color is a ***perceived quantity***,
not a direct, physical observable

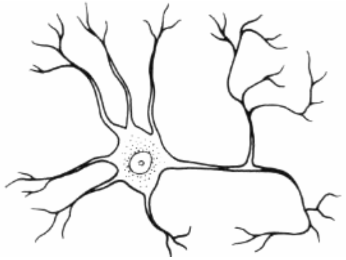
Color - A Visual Sensation

object

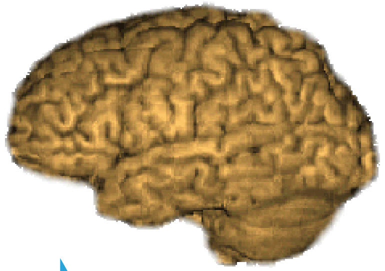


light stimulus

eye



nerve signal



brain

electromagnetic rays → color sensation

realm of direct observables

realm of psychology

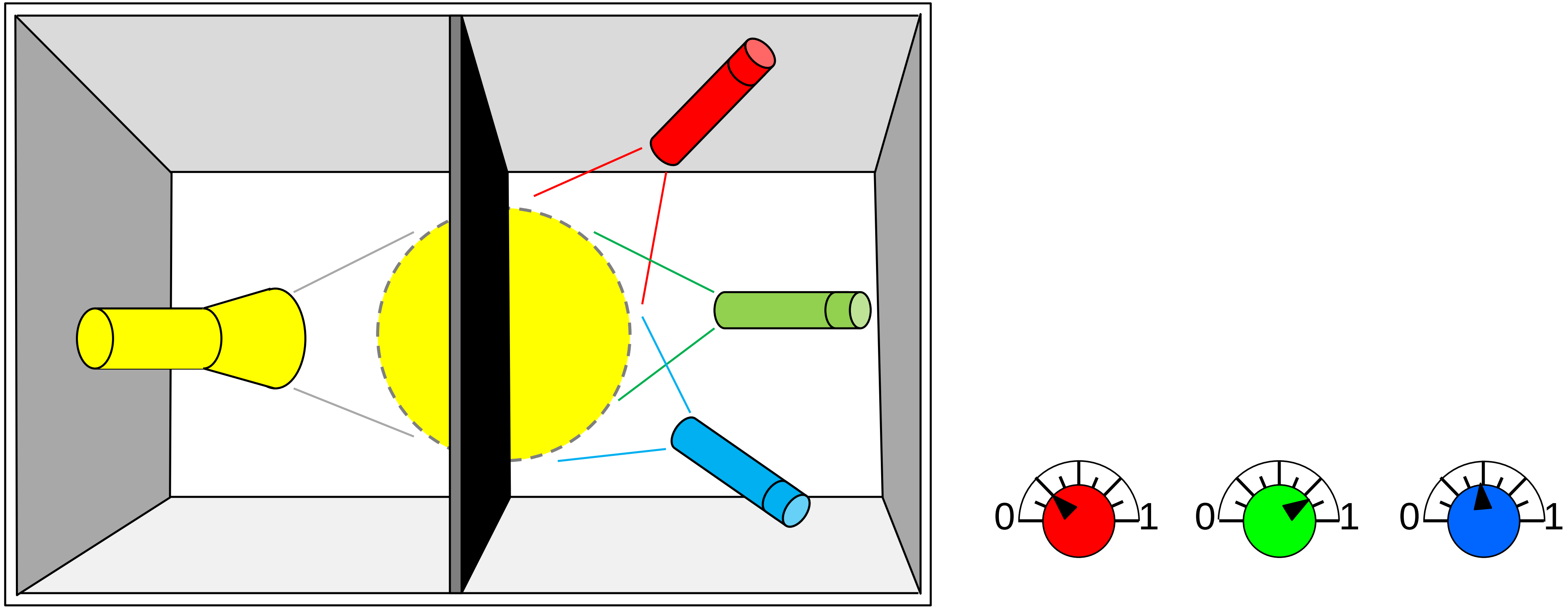
Colorimetry

- Colorimetry is the branch of color science concerned with ***numerically specifying*** the color of a physically defined visual stimulus in such manner that
  - stimuli with the same specification look alike
    (under the same viewing conditions)
  - stimuli that look alike have the same specification
  - numbers used are *continuous* functions of the physical parameters

Colorimetry Properties

- Colorimetry only considers the ***visual discriminability*** of physical beams of radiation
- for the purposes of Colorimetry a „color“ is an equivalence class of mutually ***indiscriminable beams***
- colors in this sense cannot be said to be “red”, “green” or any other “color name”
- discriminability is decided before the brain
  - Colorimetry is not psychology

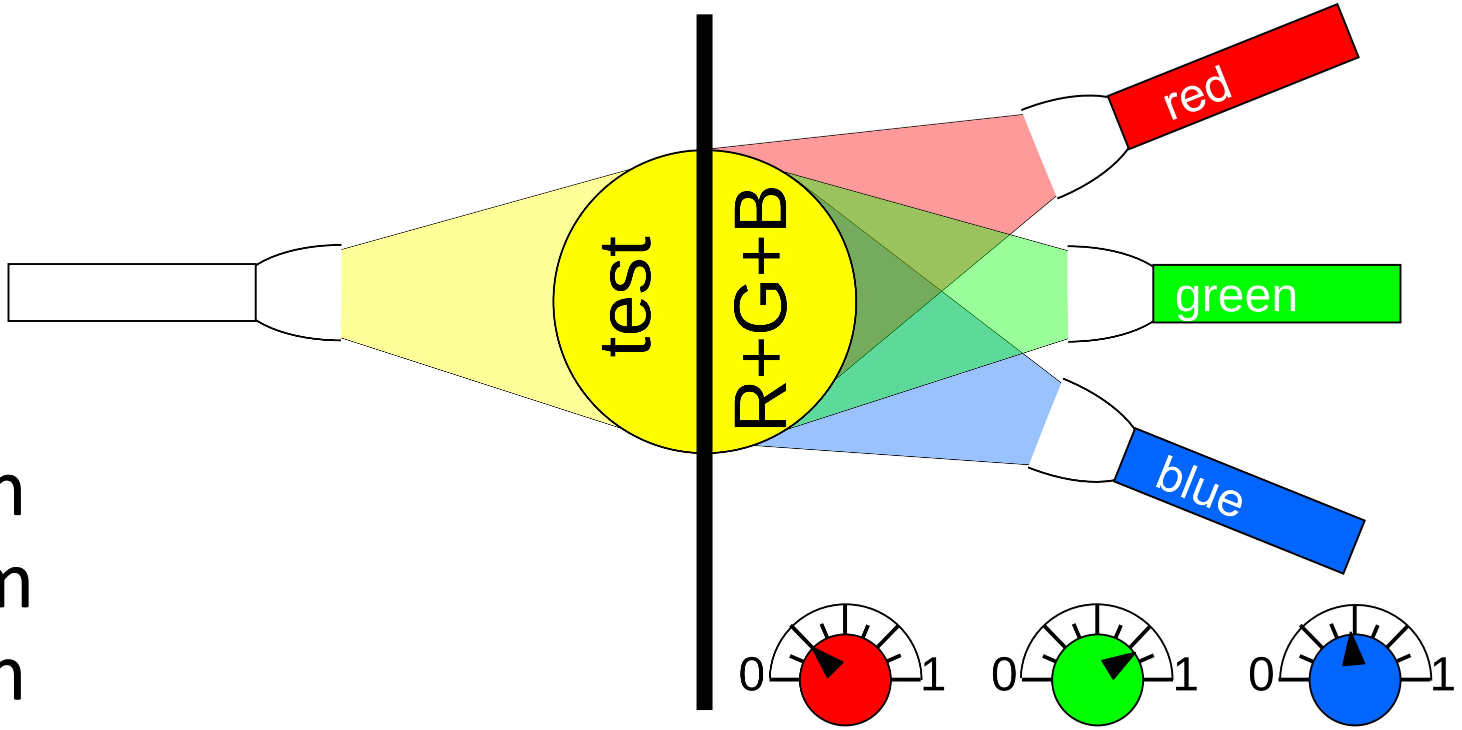
- observers had to match *(monochromatic)* test lights by combining 3 fixed primaries



- test box: compare test light with combined light

Color Matching Experiments

- observers had to match *(monochromatic)* test lights by combining 3 fixed primaries

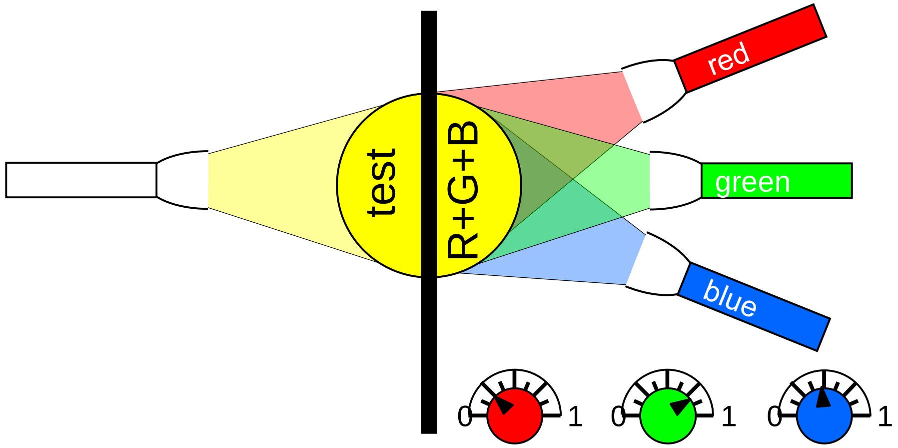


R = 700.0 nm
G = 546.1 nm
B = 435.8 nm

- goal: find the ***unique*** RGB coordinates for each stimulus

Tristimulus Values

- the values R_Q, G_Q and B_Q of a stimulus Q that fulfill



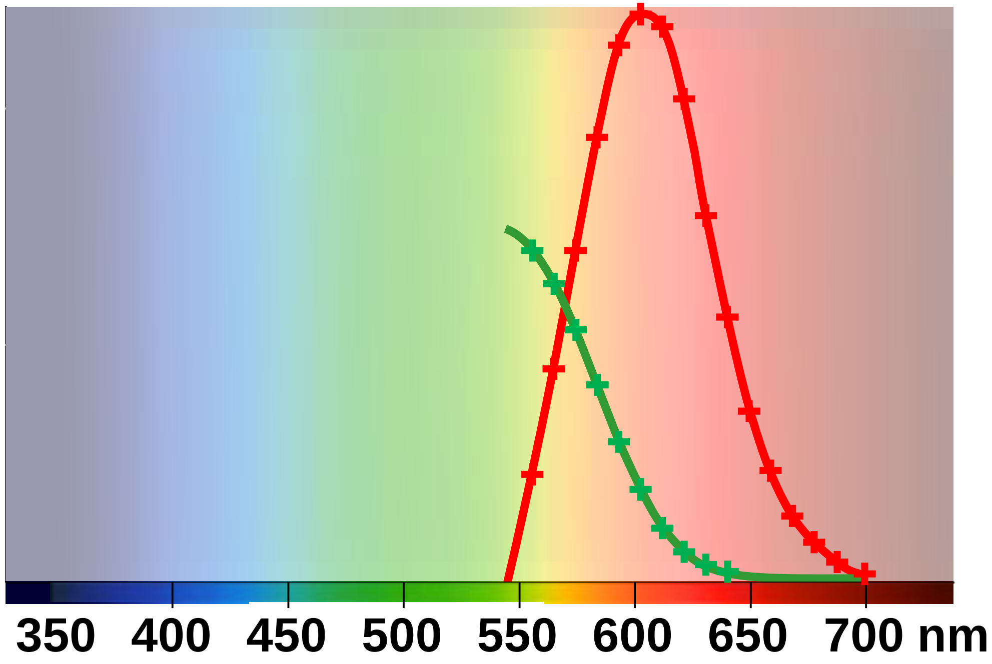
$$Q = R_Q \cdot R + G_Q \cdot G + B_Q \cdot B$$

are called the ***tristimulus values*** of Q

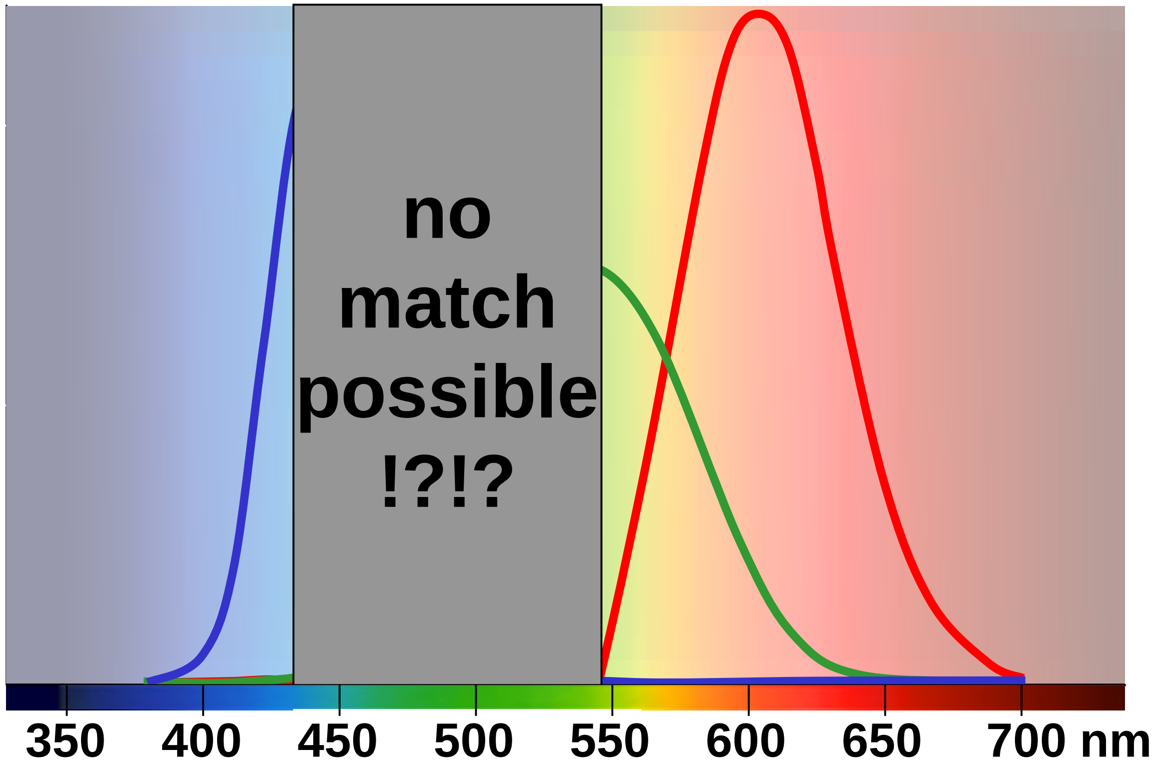
- in case of a ***monochromatic*** stimulus Q_λ the values R_λ, G_λ and B_λ are called ***spectral tristimulus values***

Color Matching Procedure

- (1) test field = 700 nm-red with radiance P_{ref}
  - observer adjusts luminance of R (G=0, B=0)
- (2) test light wavelength is decreased in constant steps (radiance P_{ref} stays the same)
  - observer adjusts R, G, B
- (3) repeat for entire visible range



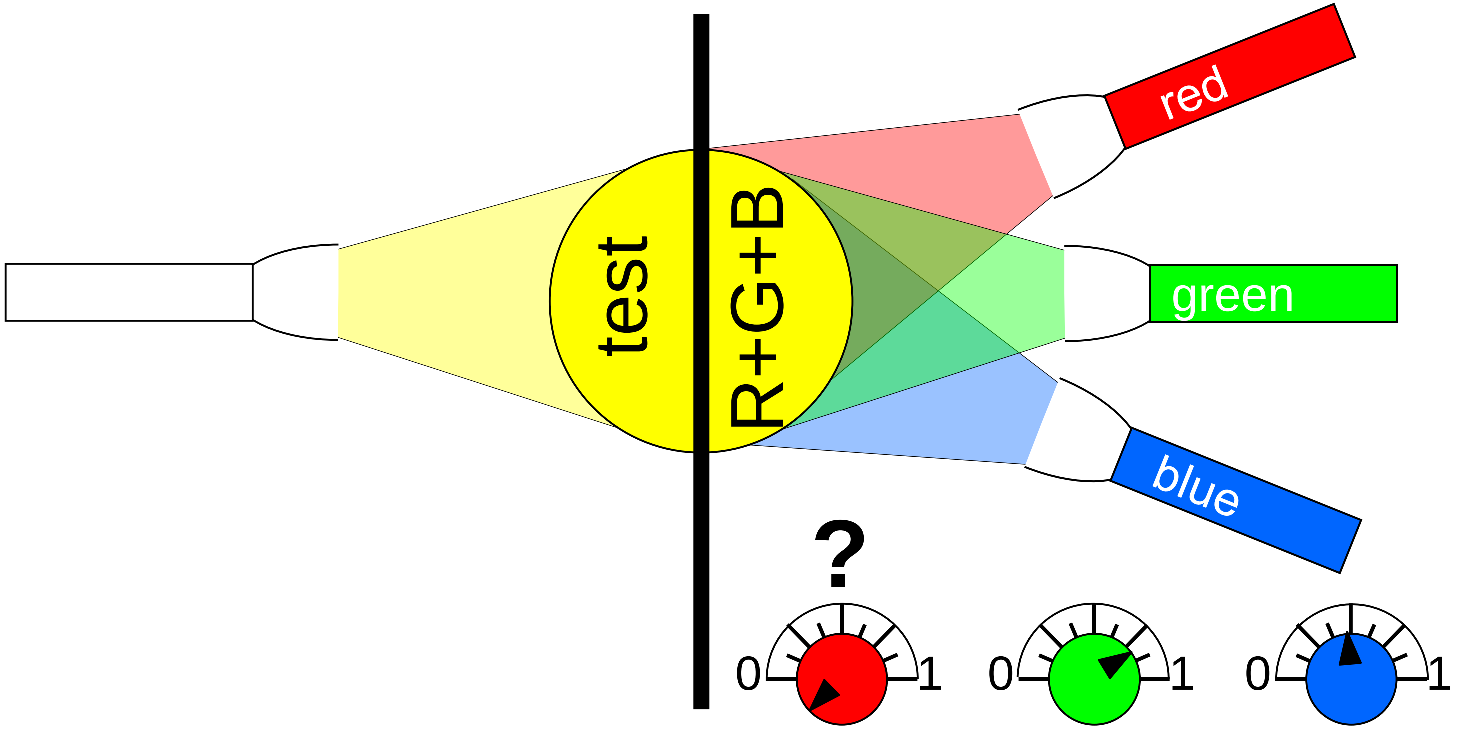
Color Matching Result !?



- observers want to „subtract“ red light from the match side...!?

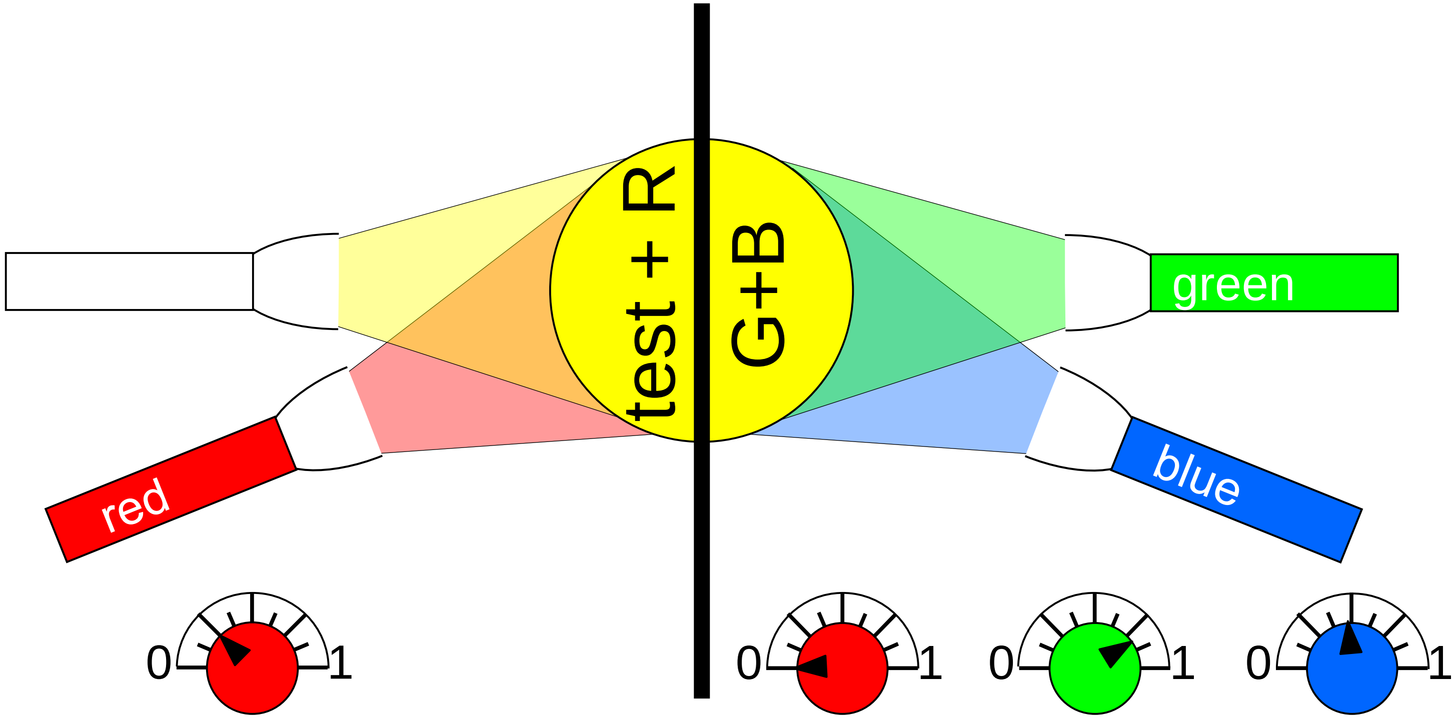
Color Matching Experiment Problem

- for some colors observers want to reduce red light to negative values…!?
- but there is no negative light…!

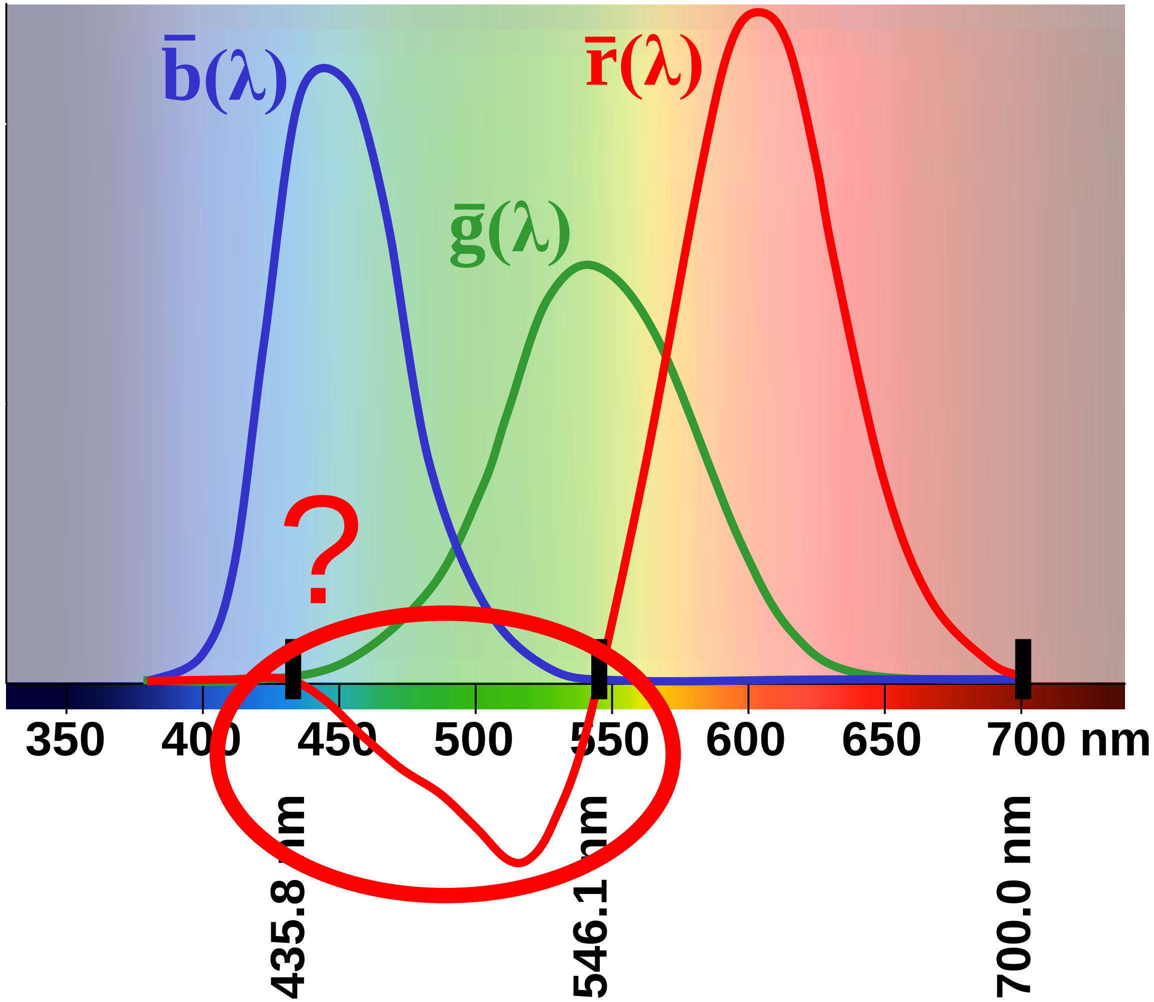


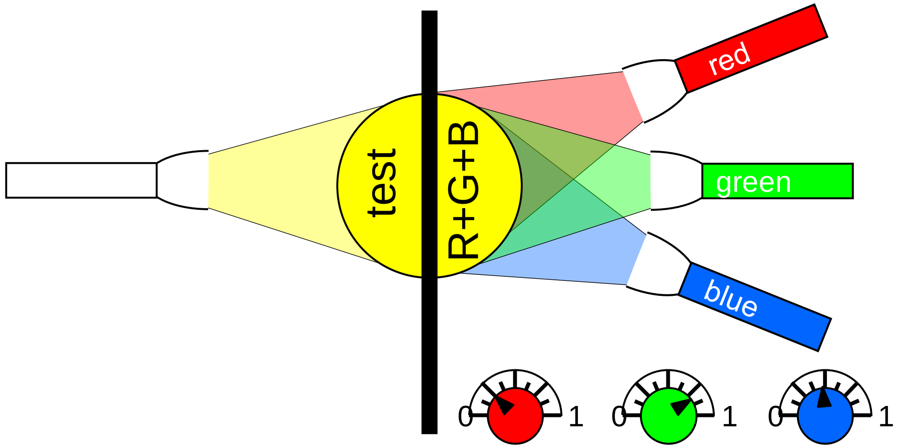
“Negative” Light in a Color Matching Exp.

- if a match using only positive RGB values proved impossible, observers could simulate a ***subtraction*** of red from the match side by adding it to the test side



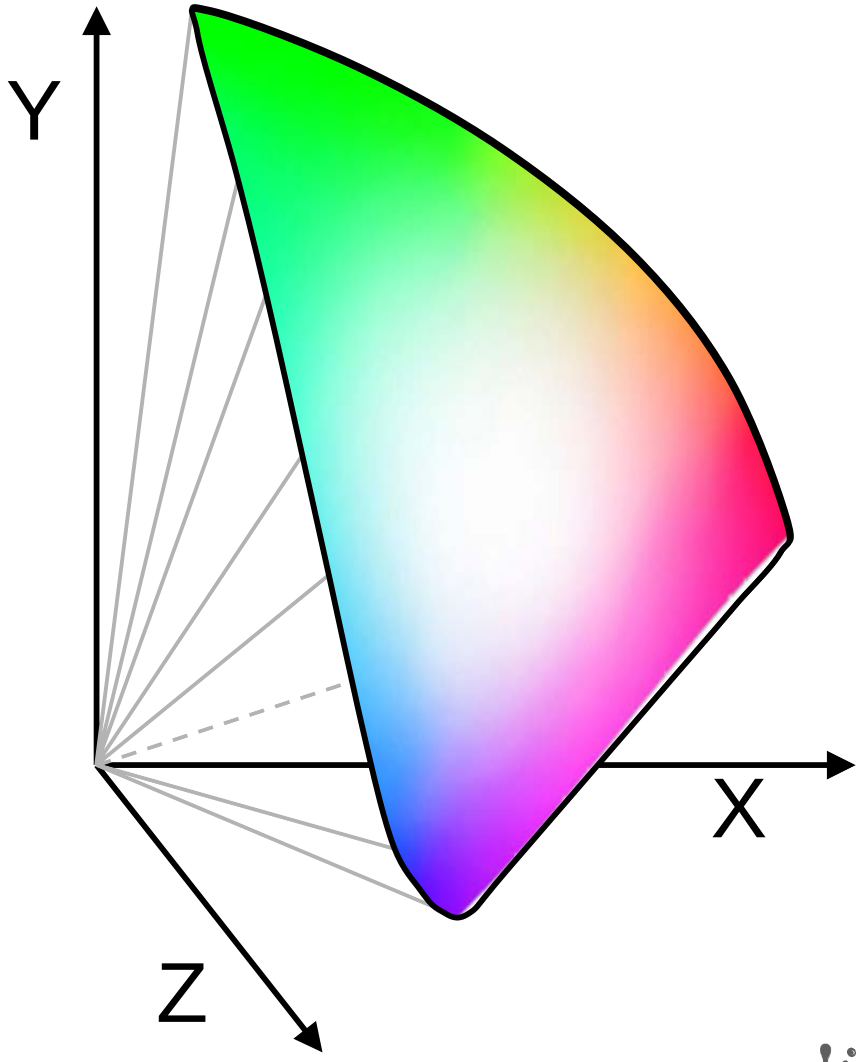
CIE RGB Color Matching Functions





CIE XYZ

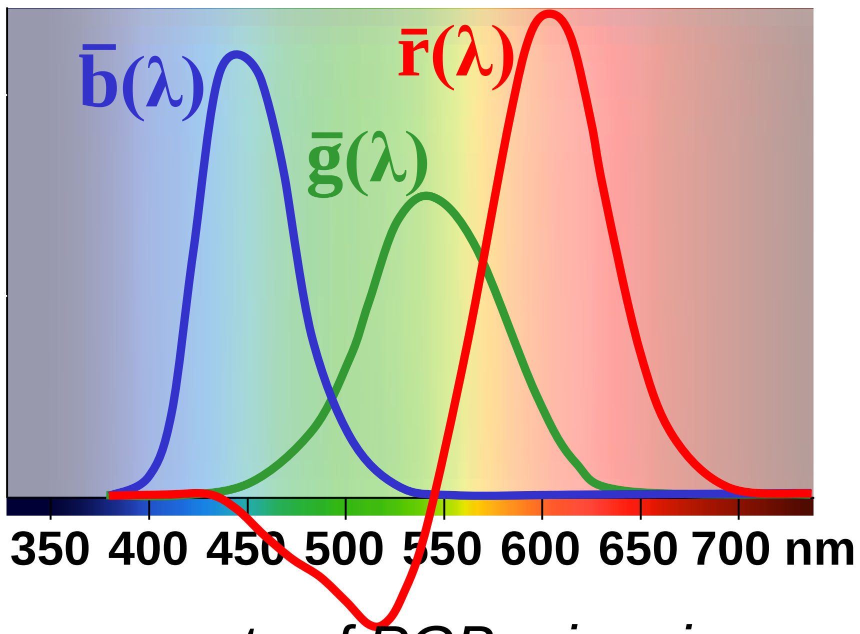
- problem solution: ***XYZ color system***
- tristimulus system derived from RGB
- based on 3 *imaginary* primaries
- all 3 primaries are *imaginary* colors
- only positive XYZ values can occur!
- 1931 by **CIE**
  (**C**ommission **I**nternationale de l'**E**clairage)



RGB vs. XYZ

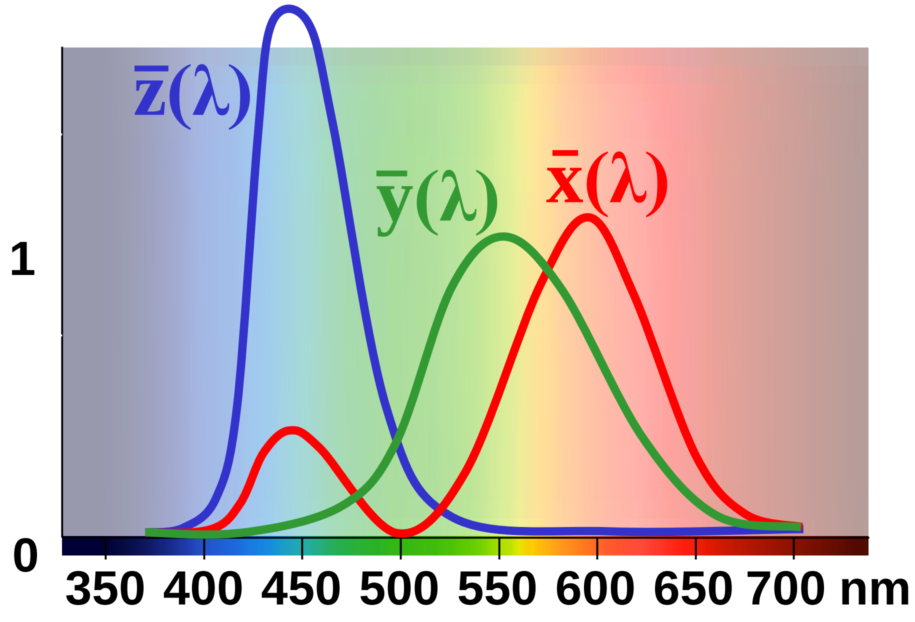
- negative component disappears
- $\bar{y}(\lambda)$ is the achromatic luminance sensitivity

RGB system



amounts of RGB primaries needed to display spectral colors

XYZ system



amounts of CIE primaries needed to display spectral colors

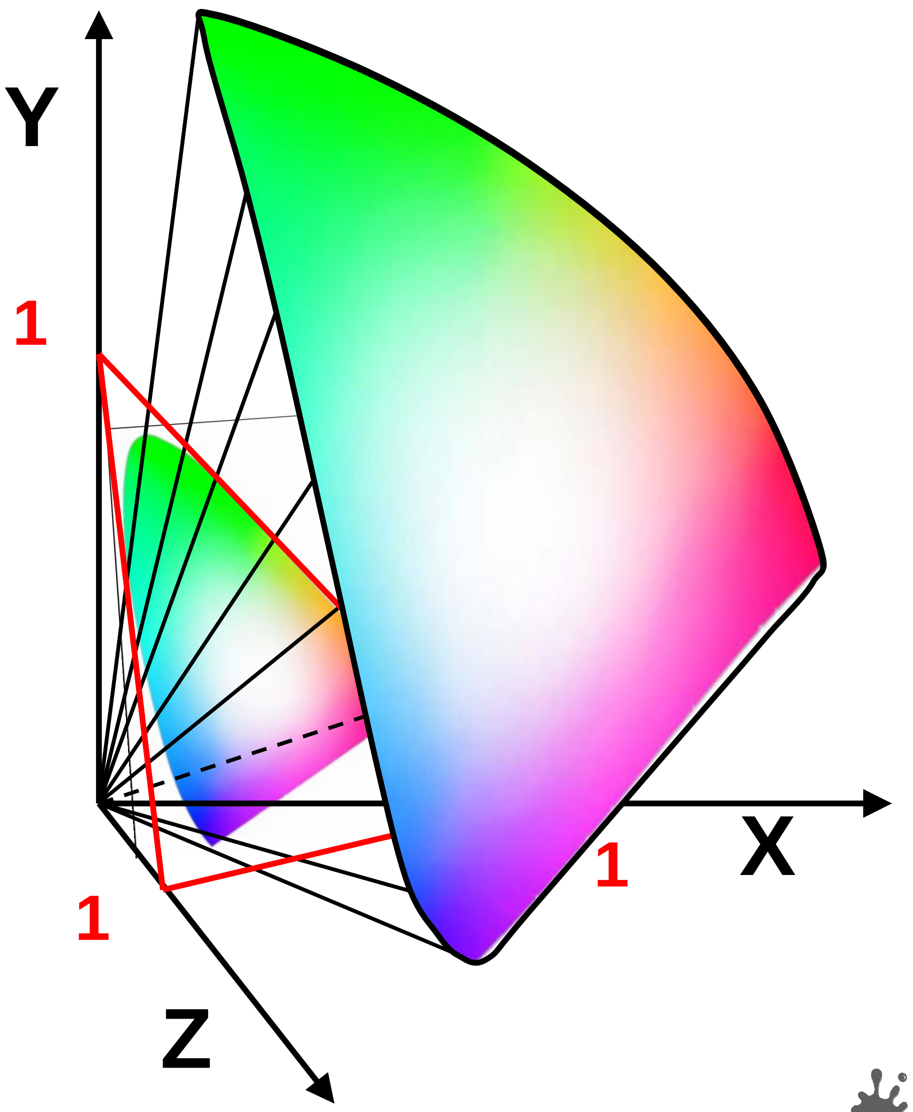
CIE Color Model Formulas

- **XYZ** color model $\quad C(\lambda) = X \cdot \mathbf{X} + Y \cdot \mathbf{Y} + Z \cdot \mathbf{Z}$
  (**X, Y, Z** are primaries)
- normalized *chromaticity values* x, y

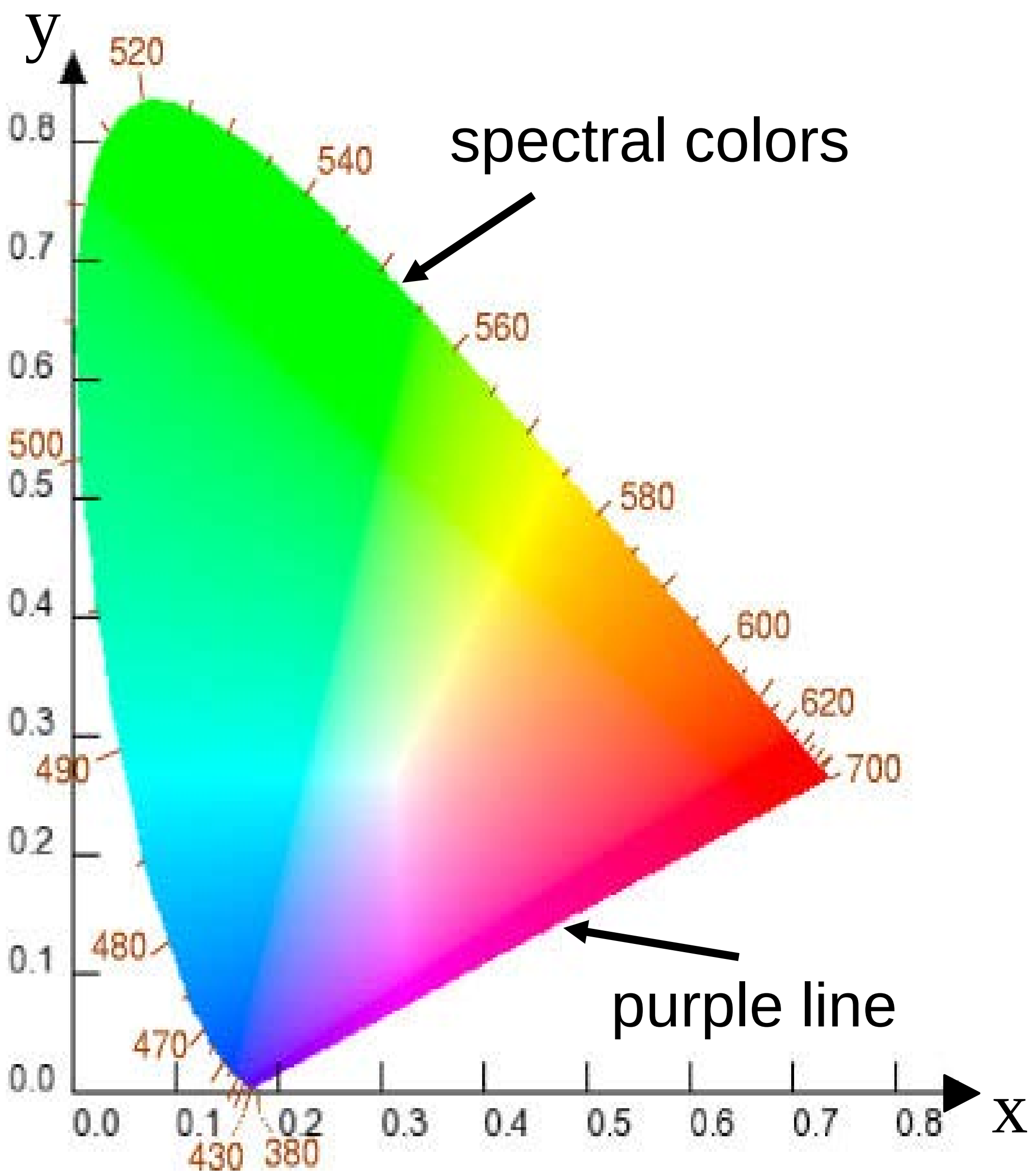
$$x = \frac{X}{X+Y+Z} \qquad y = \frac{Y}{X+Y+Z}$$

$$(\, z = 1 - x - y \,)$$

- complete description of a color: **x, y, Y**



CIE Chromaticity Diagram

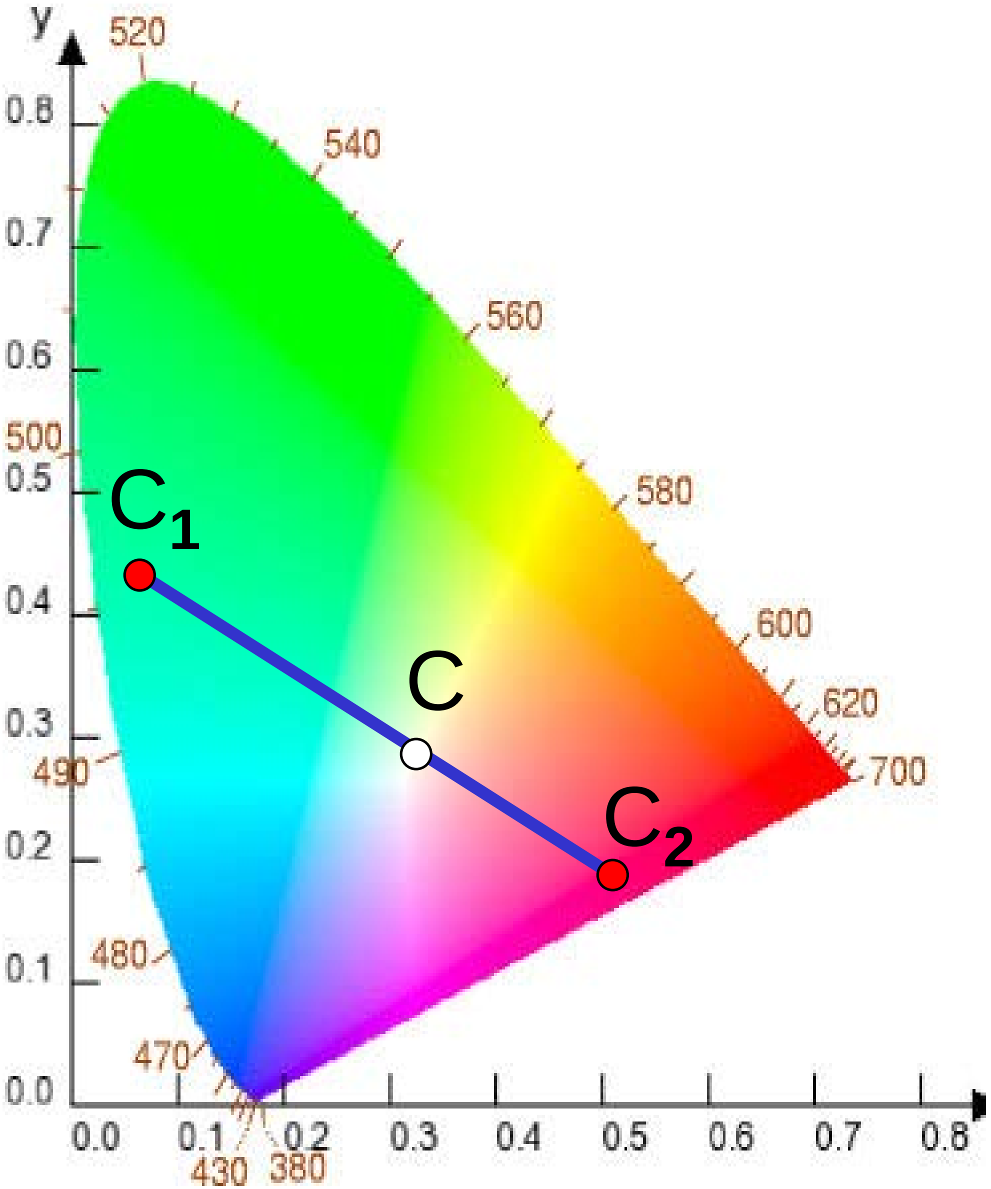


- identifying complementary colors
- determining dominant wavelength & purity
- comparing color gamuts

spectral color positions are along the boundary curve

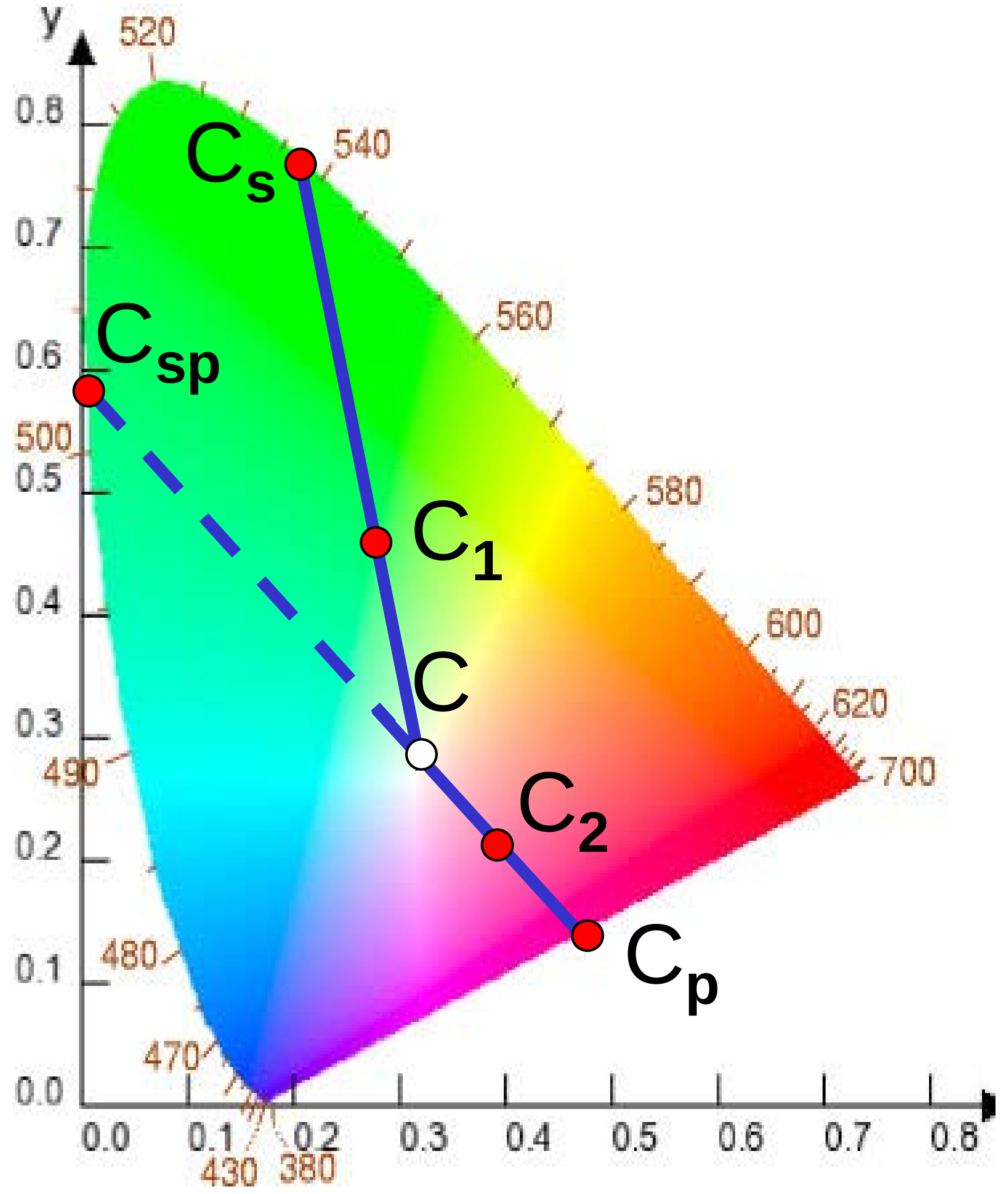
purple line contains all mixtures of red and blue

Properties of CIE Diagram (2)



representing complementary colors in the chromaticity diagram

Properties of CIE Diagram (3)

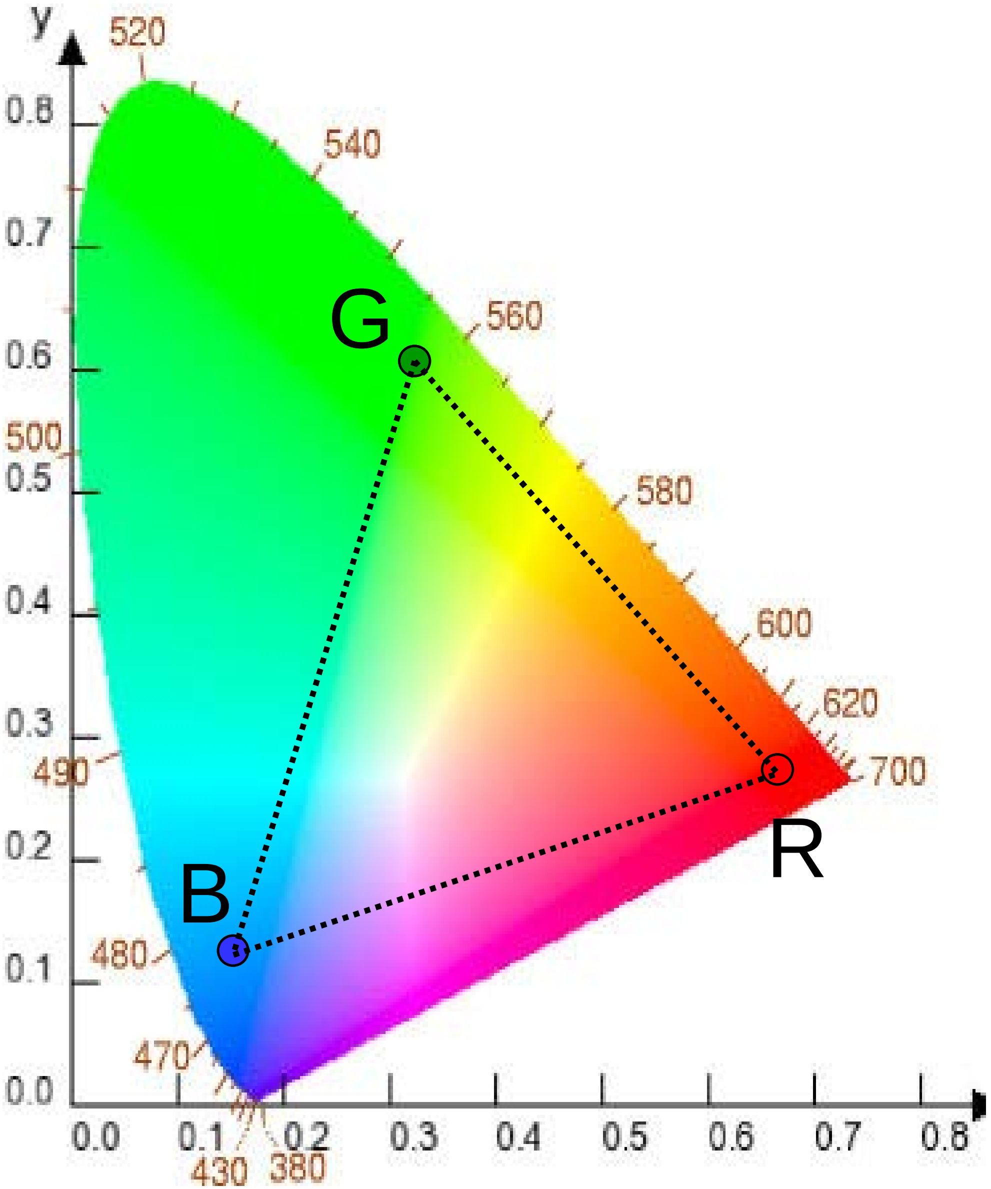


determining
dominant wavelength and purity with the chromaticity diagram

$C_1 \rightarrow C_s$

$C_2 \rightarrow C_p$?
$\rightarrow$ *complement* C_{sp}

Properties of CIE Diagram (4)



gamut of a typical RGB monitor

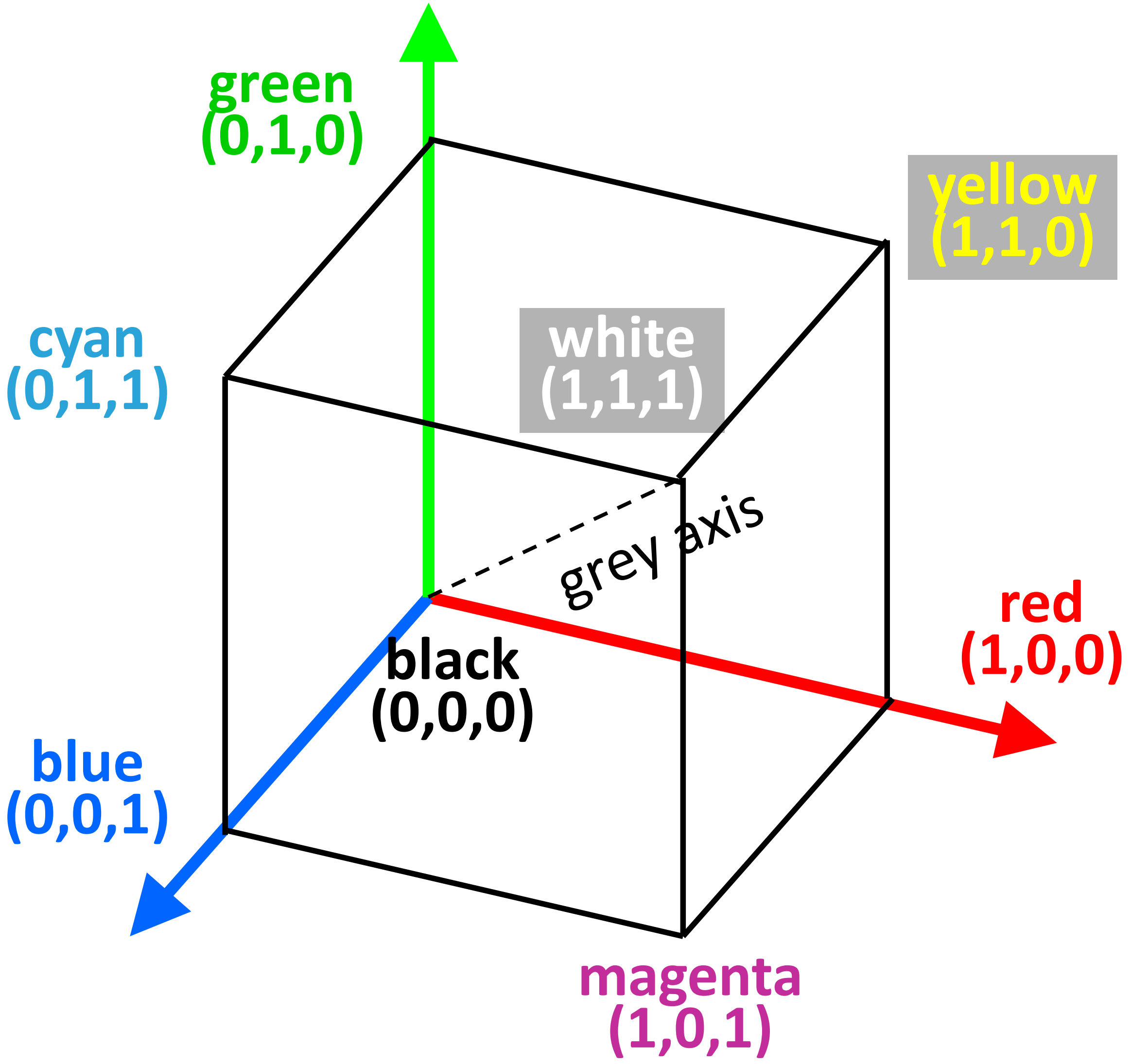
only the colors inside the triangle can be produced

Color Spaces

- **Color Metric Spaces** (CIE XYZ, L*a*b)
  - used to measure absolute values and differences - roots in colorimetry
- **Device Color Spaces** (RGB, CMY, CMYK)
  - used in conjunction with devices
- **Color Ordering Spaces** (HSV, HLS)
  - used to find colors according to some criterion

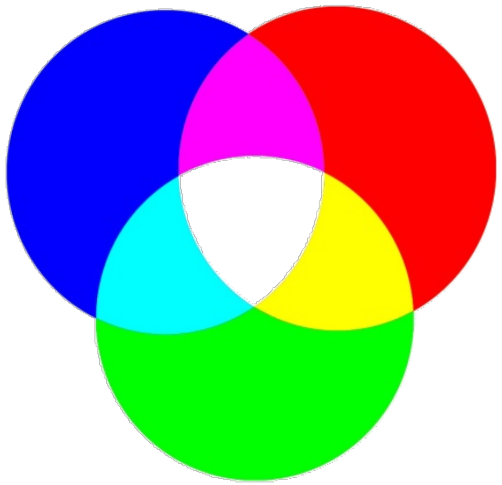
- the distinction between them is somewhat obscured by the prevalence of multi-purpose RGB in computer graphics

RGB Color Model

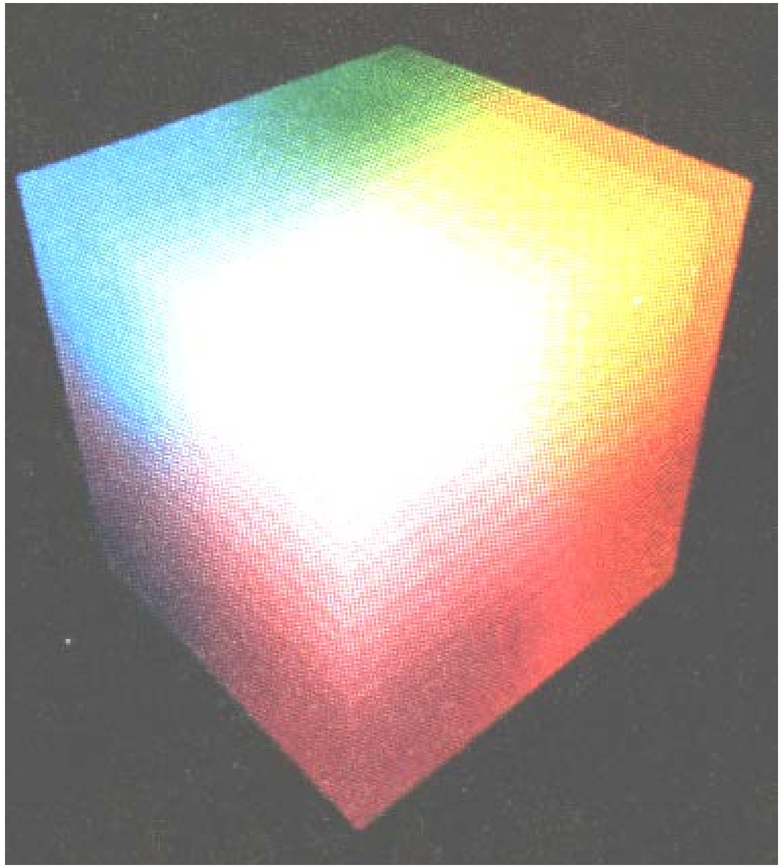


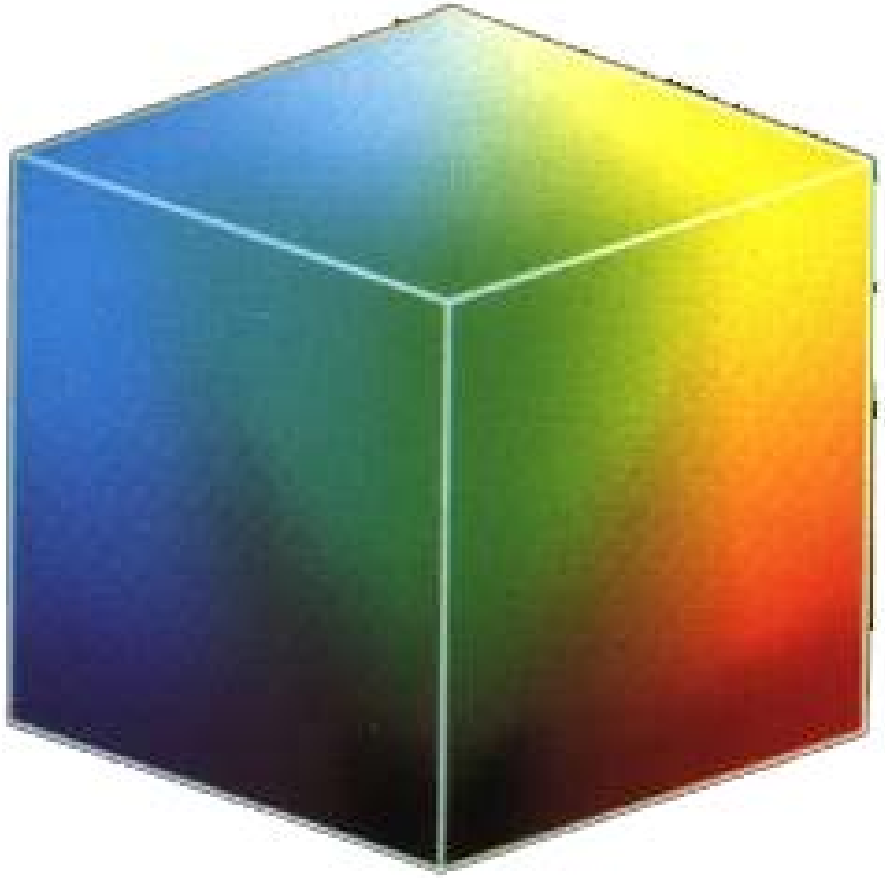
- primary colors red, green, blue
- *additive* color model (for *monitors*)

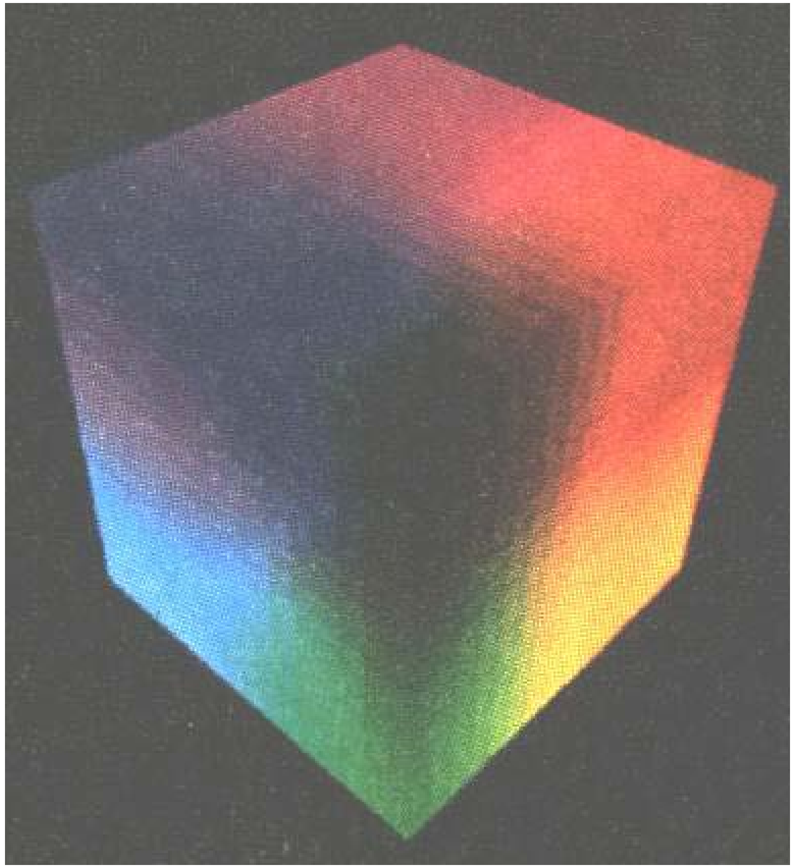
$$C(\lambda) = R \cdot \mathbf{R} + G \cdot \mathbf{G} + B \cdot \mathbf{B}$$



RGB Color Model Images

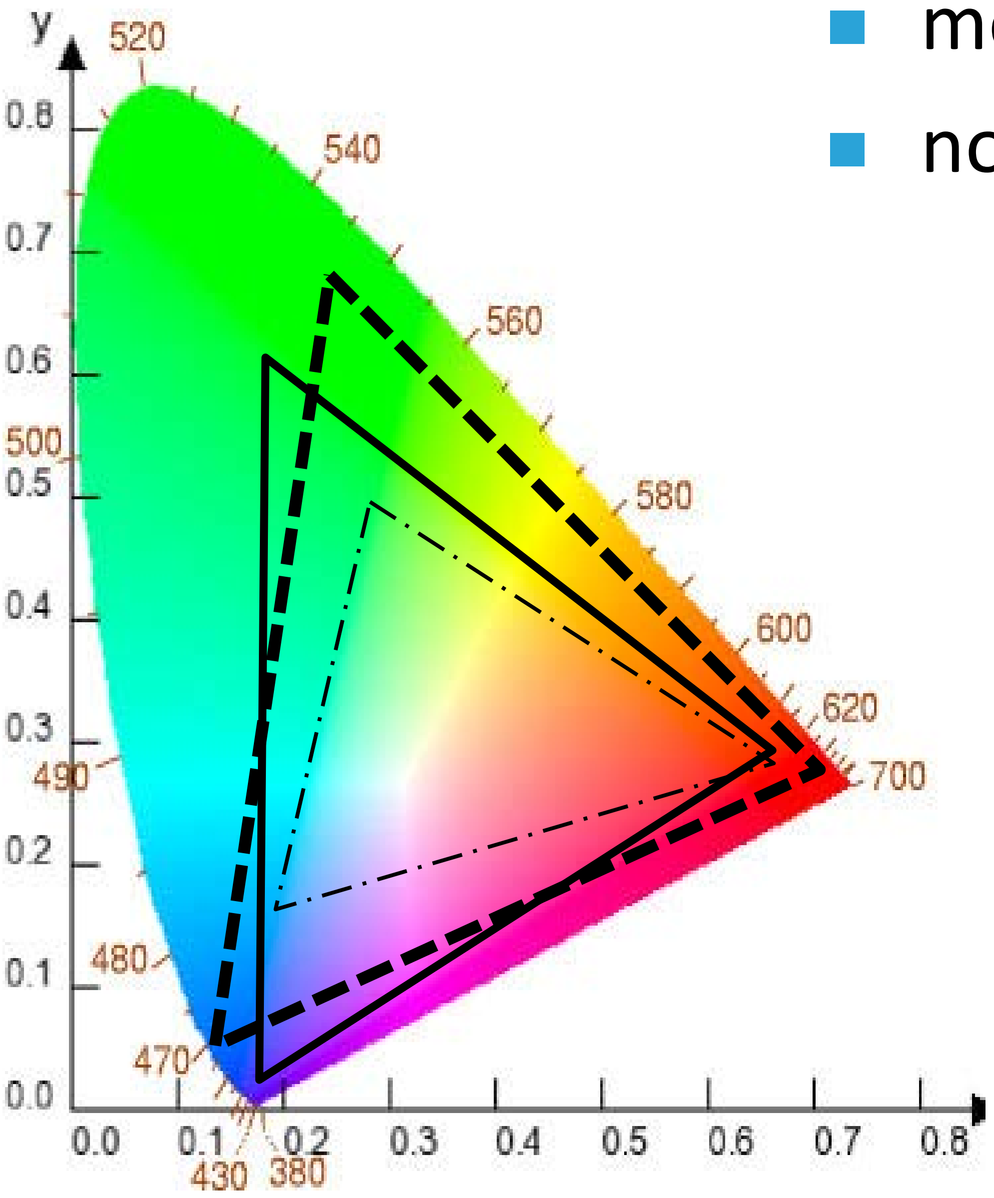






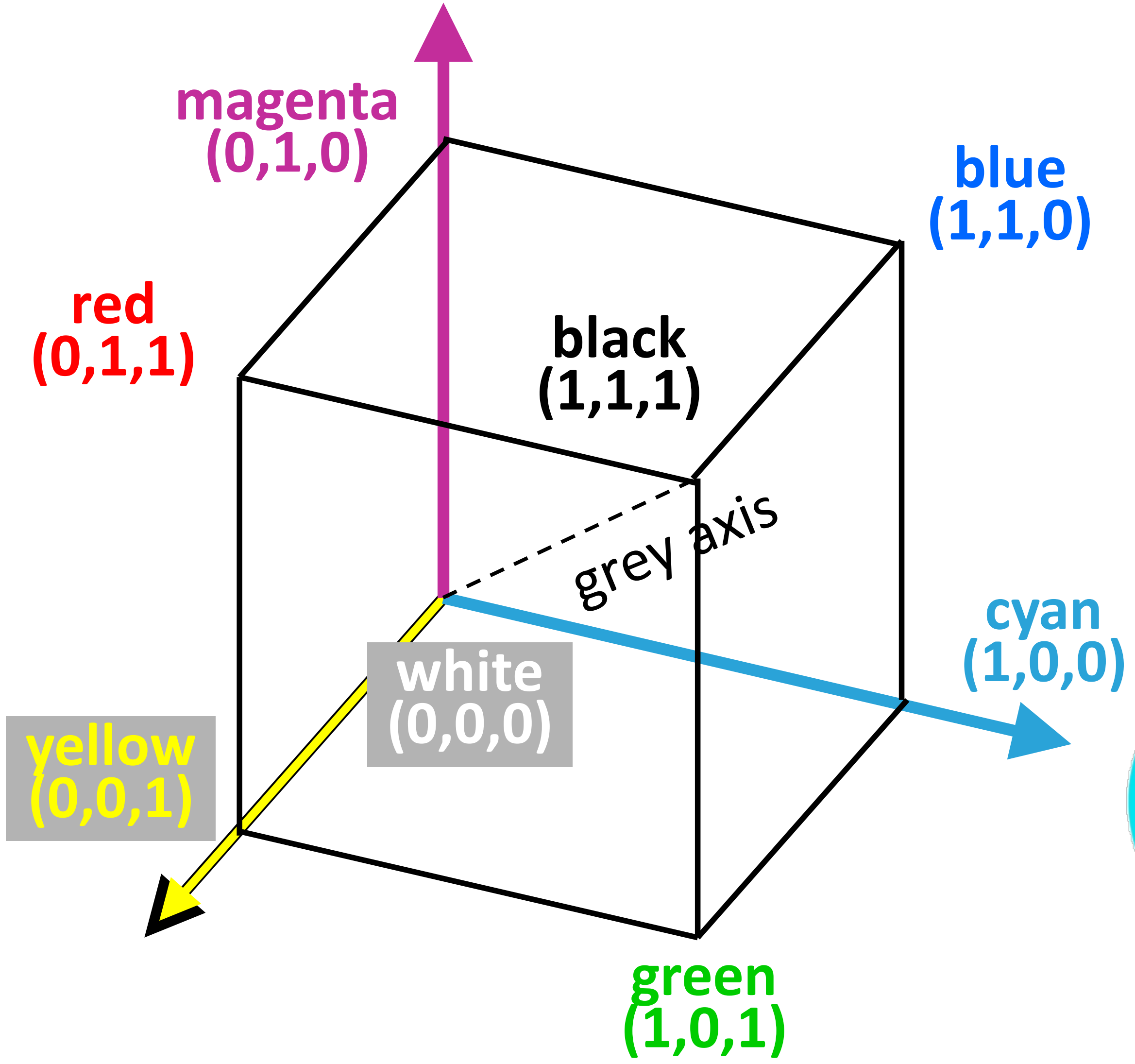
3 views of the RGB color cube

Gamuts of RGB Monitors

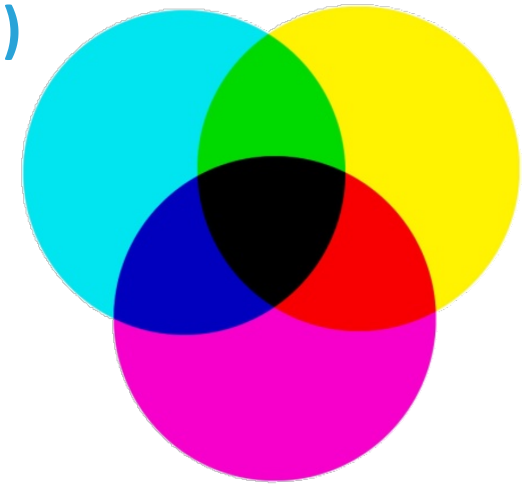


- monitor gamuts can be very different
- no monitor can display all colors

CMY Color Model

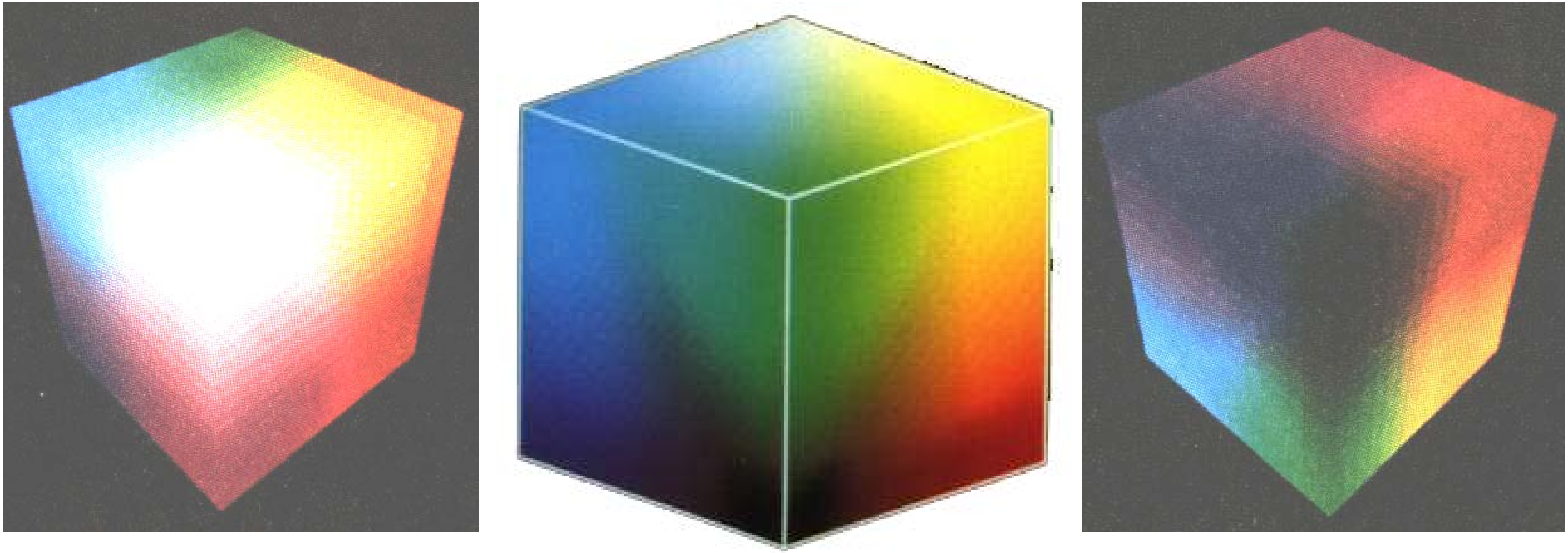


- primary colors:
  cyan, magenta, yellow
- *subtractive* color model
  (for *hardcopy devices*)
  - C = G + B, using C “subtracts” R



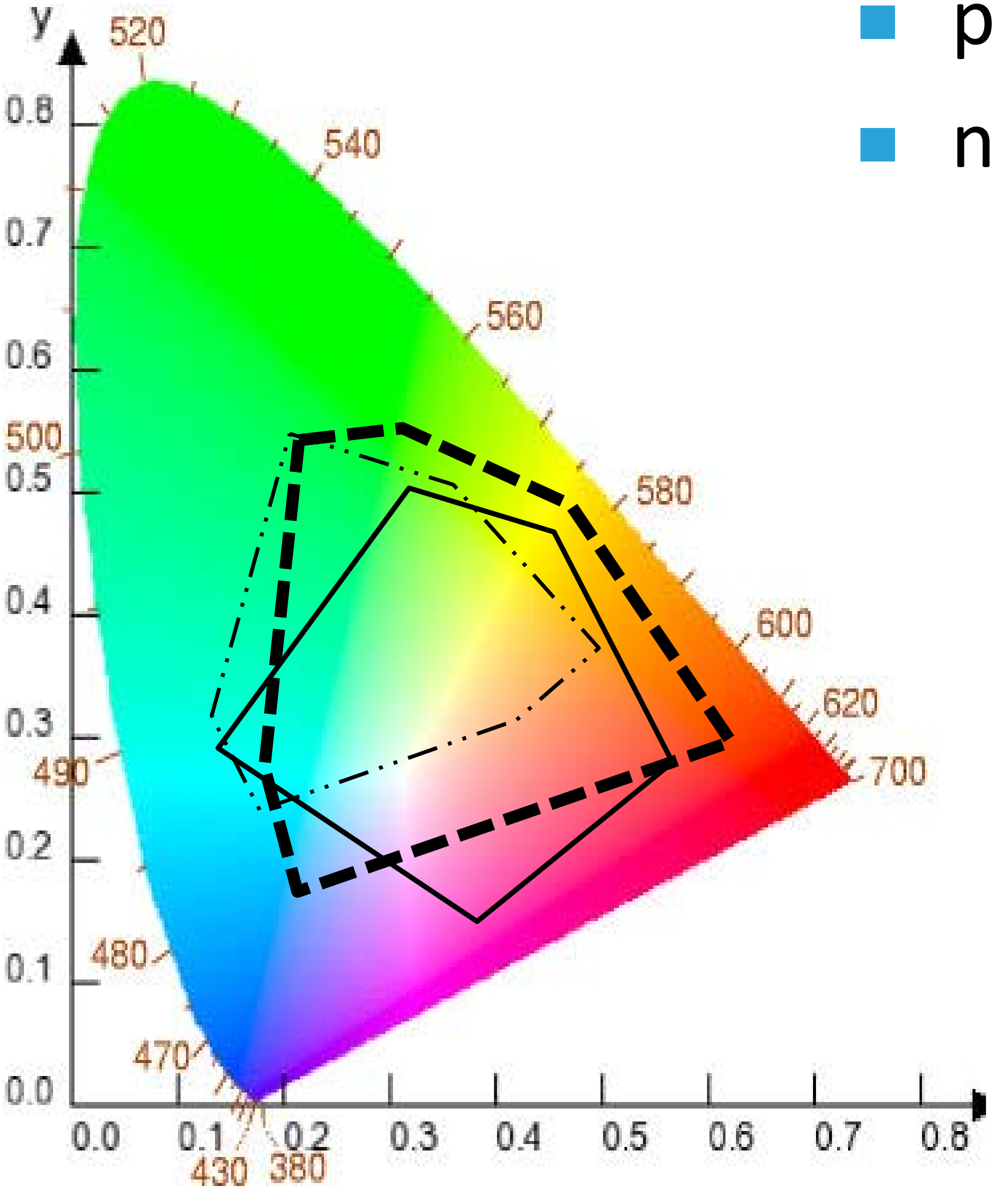
$$\begin{bmatrix} C \\ M \\ Y \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix} - \begin{bmatrix} R \\ G \\ B \end{bmatrix}$$

CMY Color Model Images



3 views of the CMY color cube

Gamuts of CMY(K) Printers



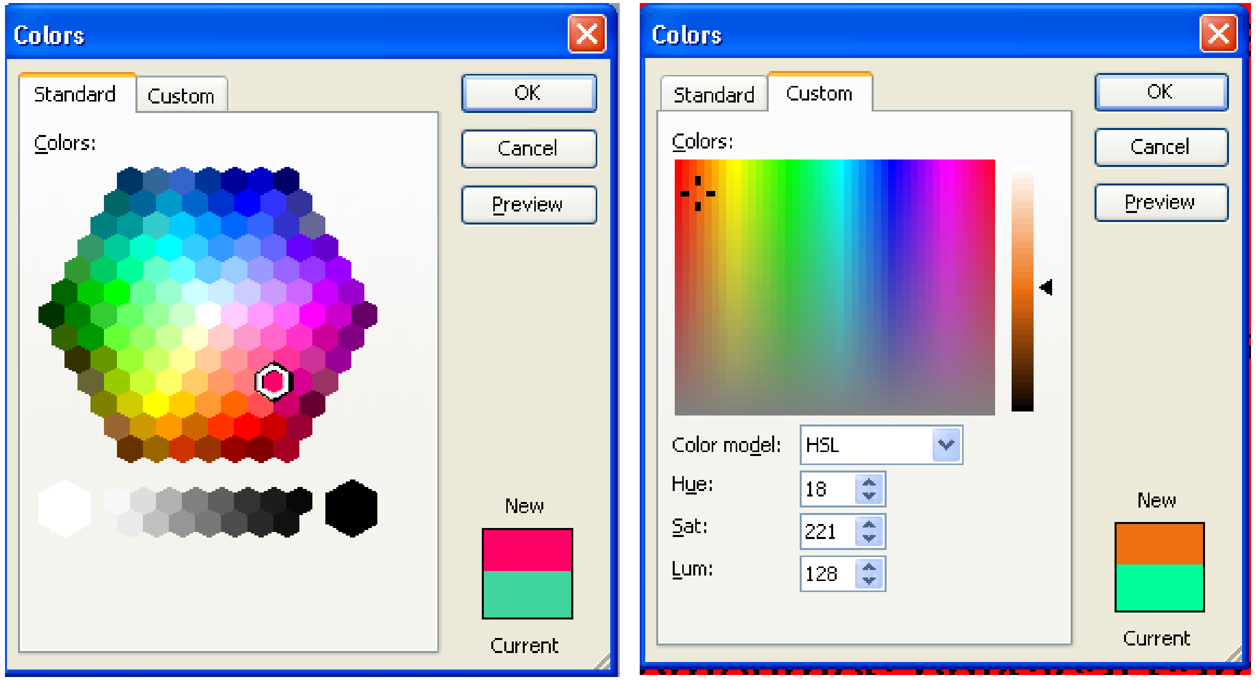
- printer gamuts can be very different
- no printer can display all colors

Color Spaces

- **Color Metric Spaces** (CIE XYZ, L*a*b)
  - used to measure absolute values and differences - roots in colorimetry
- **Device Color Spaces** (RGB, CMY, CMYK)
  - used in conjunction with devices
- **Color Ordering Spaces** (HSV, HLS)
  - used to find colors according to some criterion

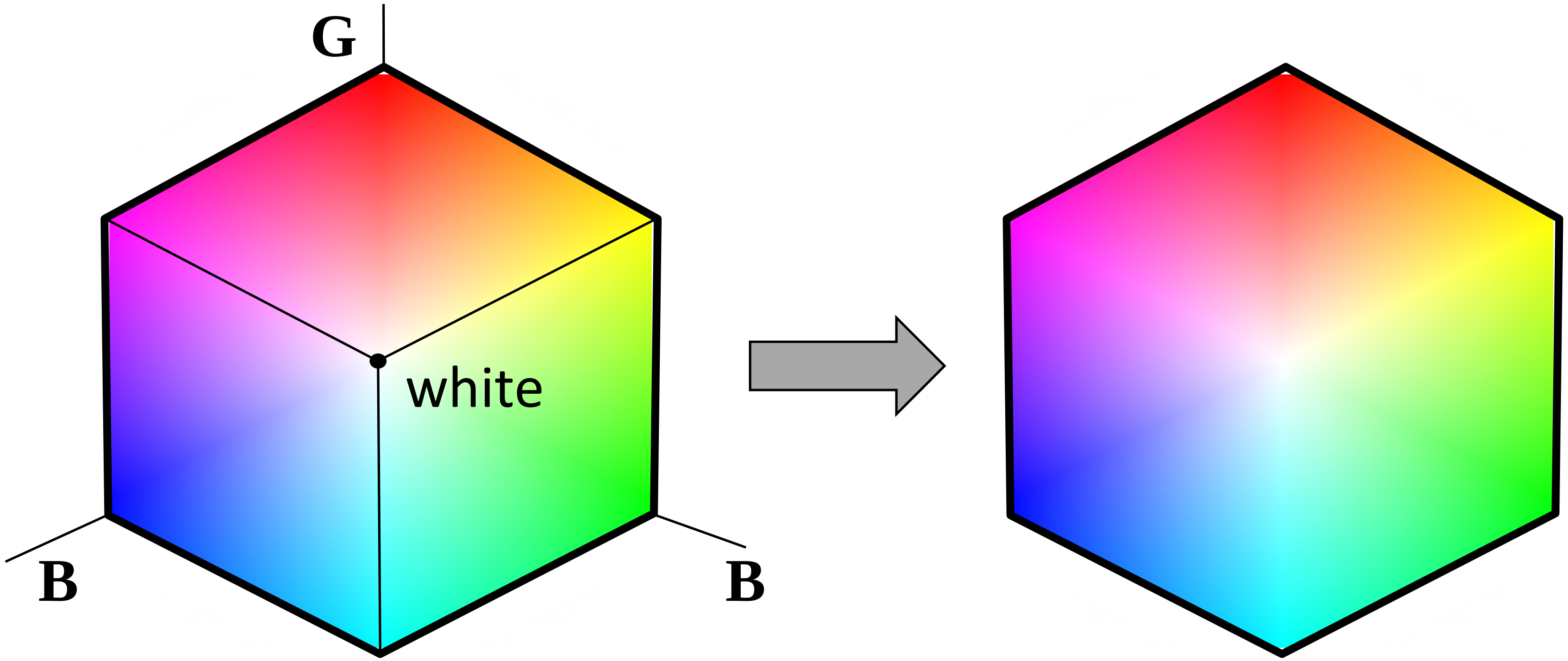
- the distinction between them is somewhat obscured by the prevalence of multi-purpose RGB in computer graphics

- **primary aim:** enable the user to intuitively choose colour values according to certain criteria
- choice can yield single or multiple colour values
- **examples:** HSV, HLS, Munsell, NCS, RAL Design, Coloroid
- used in bottom-up parts of a design process
- sometimes physical samples are provided



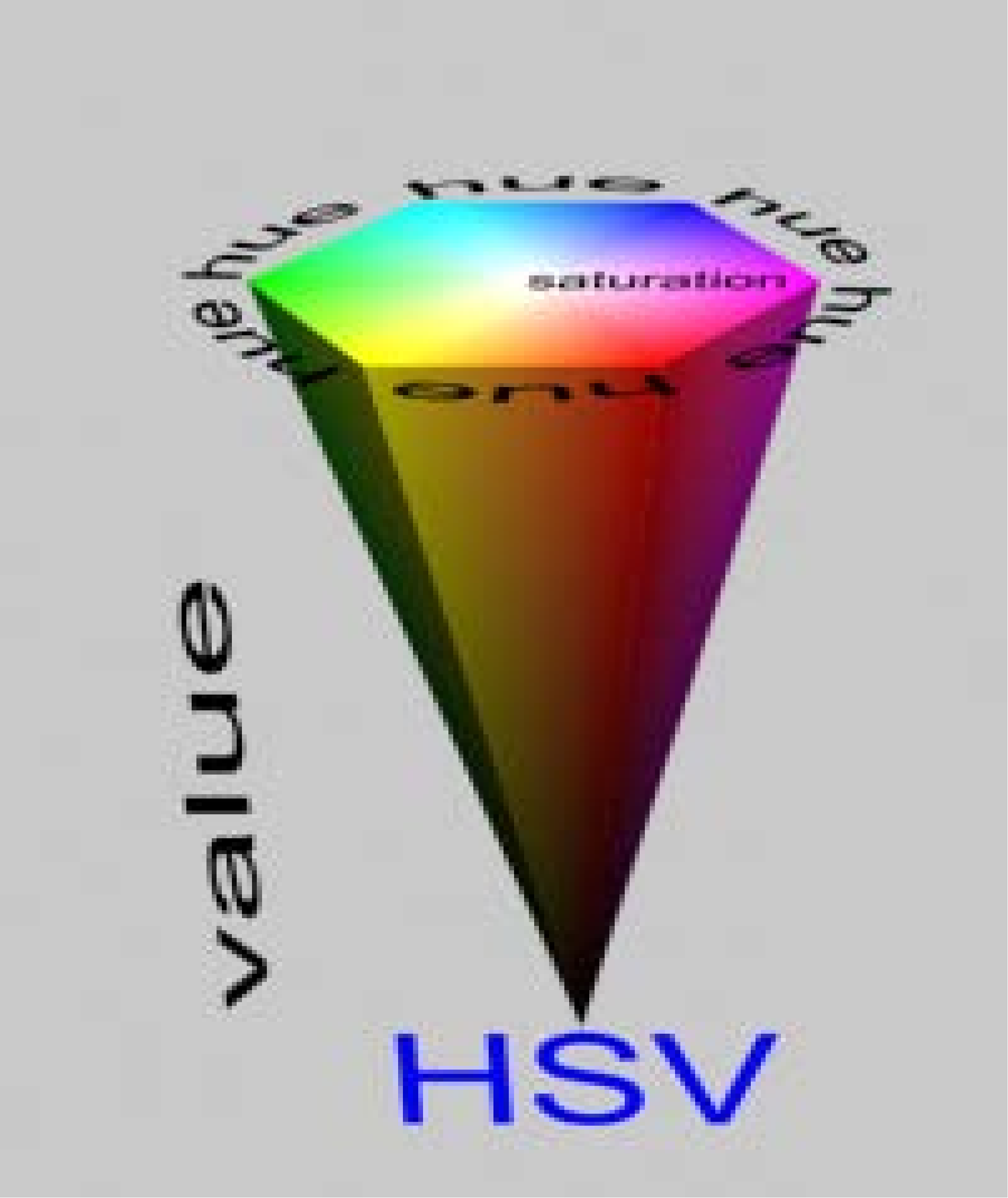
HSV Color Model

- more *intuitive* color specification
- derived from the RGB color model:
  - when the RGB color cube is viewed along the diagonal from white to black, the color cube outline is a hexagon



RGB Color Cube **Color Hexagon**

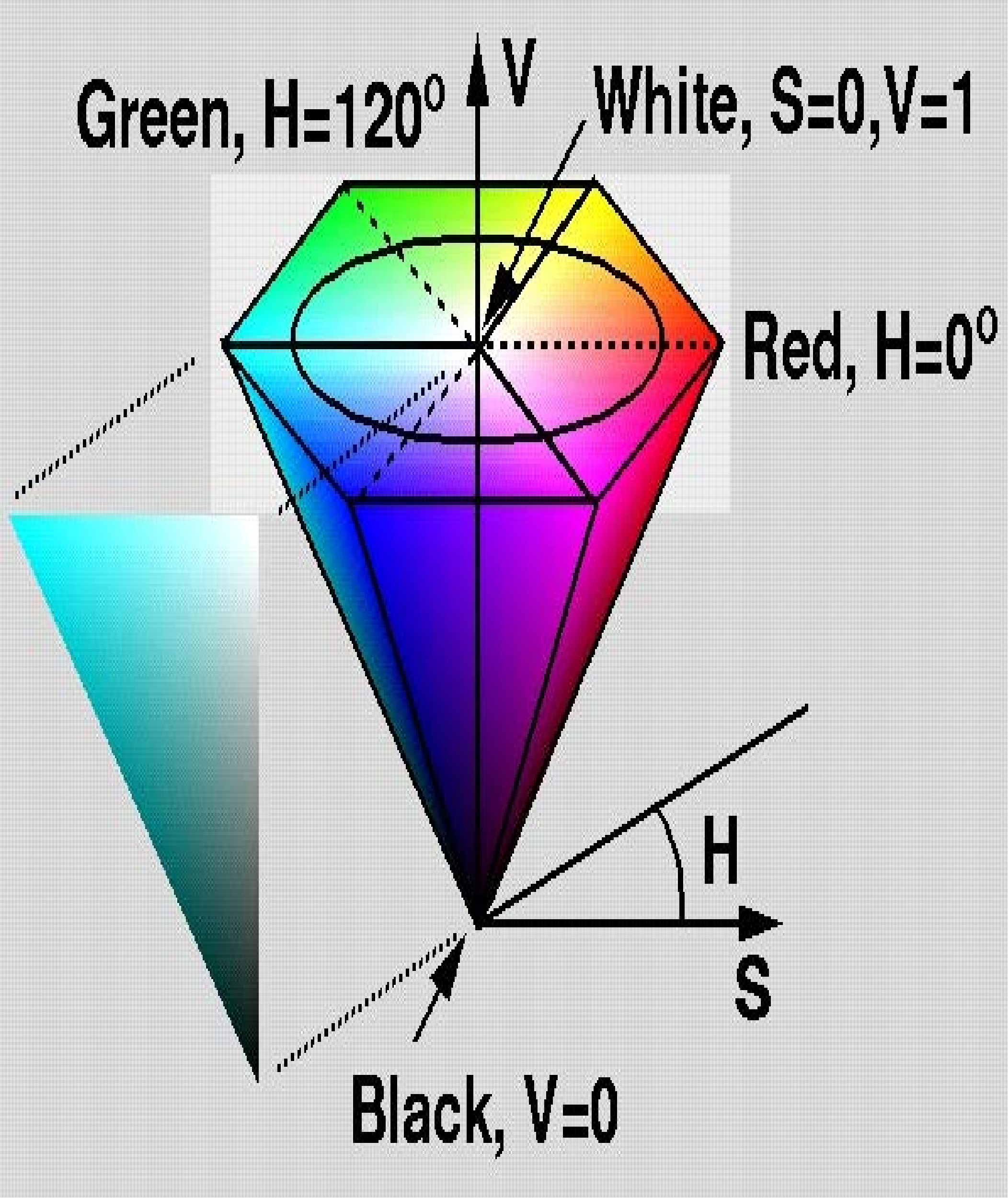
HSV Color Model Hexcone



- color components:
  - hue (H) $\in [0°, 360°]$
  - saturation (S) $\in [0, 1]$
  - value (V) $\in [0, 1]$

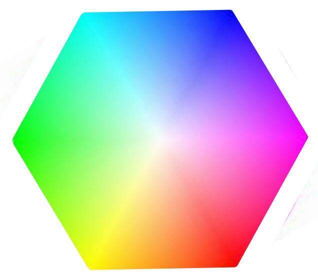
HSV hexcone

HSV Color Model Hexcone

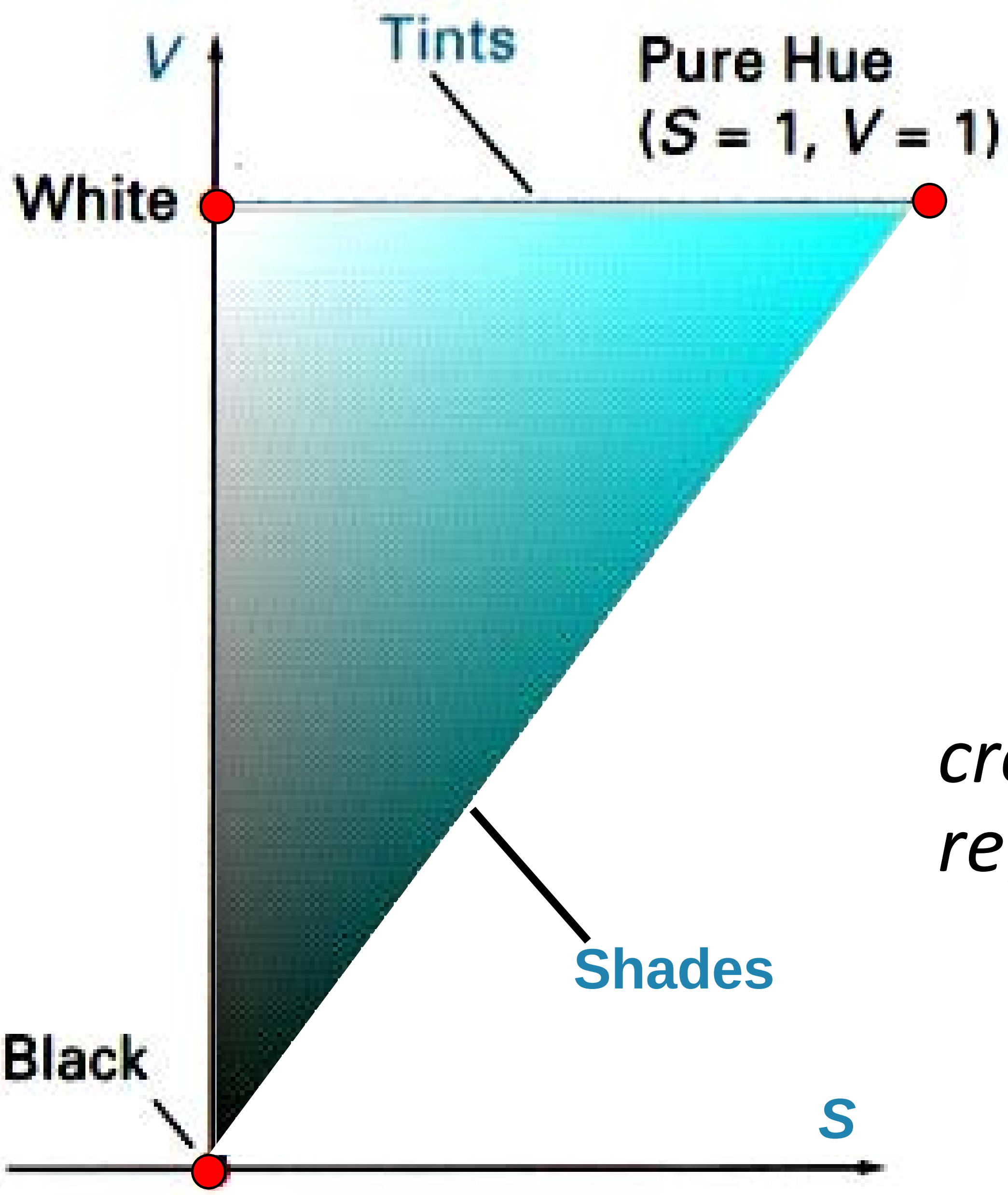


- color components:
  - hue (H) $\in [0°, 360°]$
  - saturation (S) $\in [0, 1]$
  - value (V) $\in [0, 1]$

HSV hexcone



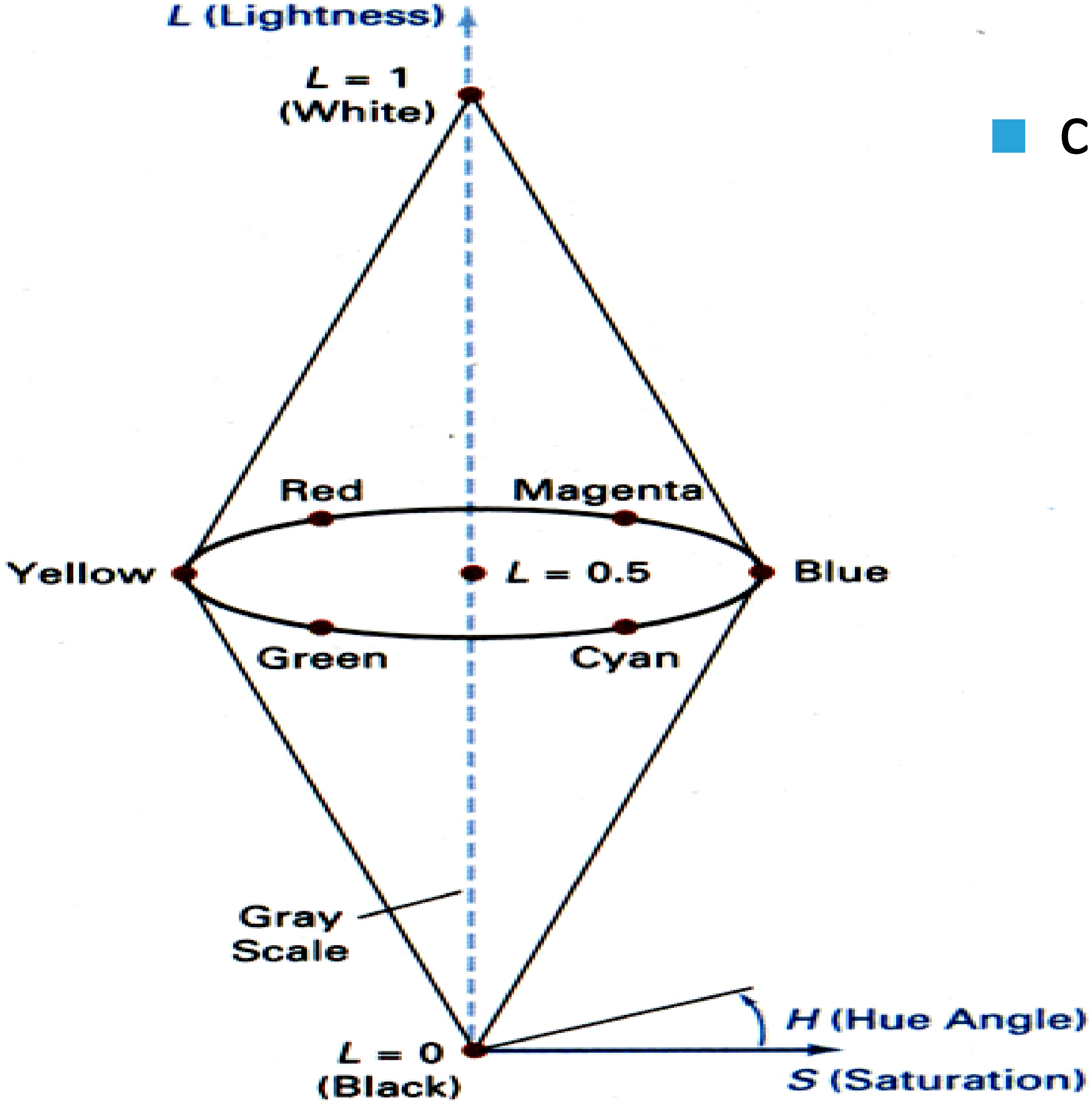
HSV Color Definition



- color definition
  - select hue, S=1, V=1
  - add black pigments, i.e., decrease V
  - add white pigments, i.e., decrease S

cross section of the HSV hexcone showing regions for shades, tints, and tones

HLS Color Model

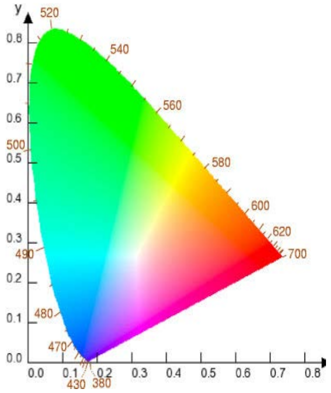


- color components:
  - hue (H) ∈ [0°, 360°]
  - lightness (L) ∈ [0, 1]
  - saturation (S) ∈ [0, 1]

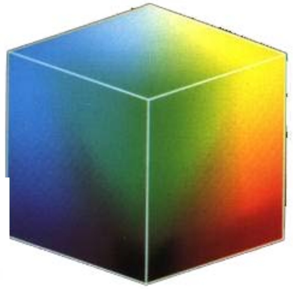
HLS double cone

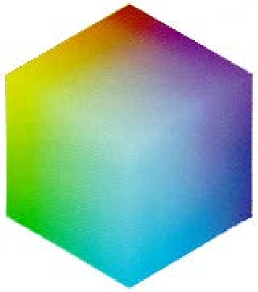
Color Model Summary

- **Colorimetry**:
  - **CIE XYZ**: contains all visible colors

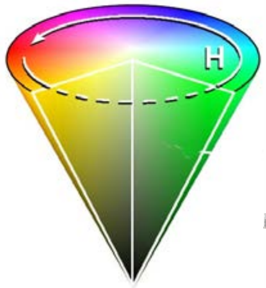


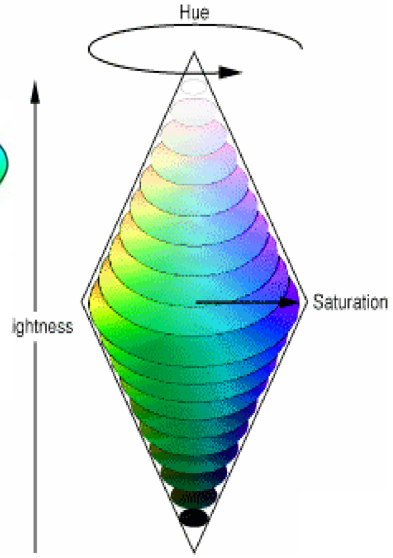
- **Device Color Systems**:
  - **RGB**: *additive* device color space (monitors)
  - **CMY(K)**: *subtractive* device color space (printers)





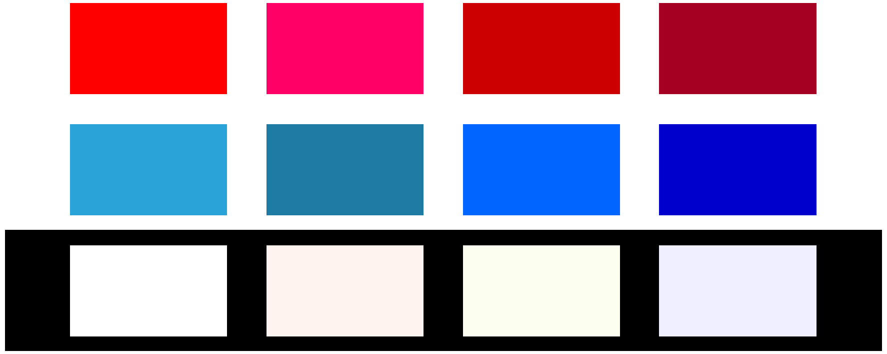
- **Color Ordering Systems**:
  - **HSV**, **HLS**: for user interfaces





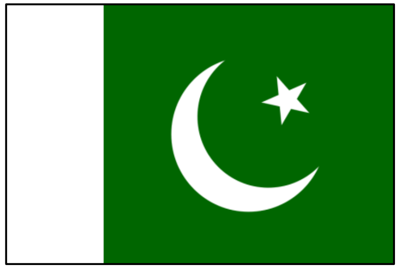
Color Symbolism: Some Aspects

- 6 to 11 basic colors
- categories, hierarchies
- dependent on context / application
- large variation in use
  - what is red?
  - what is blue?
  - what is white? !



Color in Religion

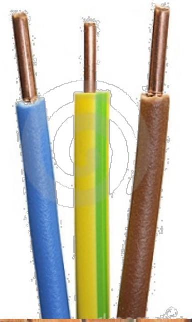
- Islam: green
- Buddhism: yellow, orange, red & purple
- Hinduism: orange, blue & blue-violet
- Christs: liturgical colors without theological connex

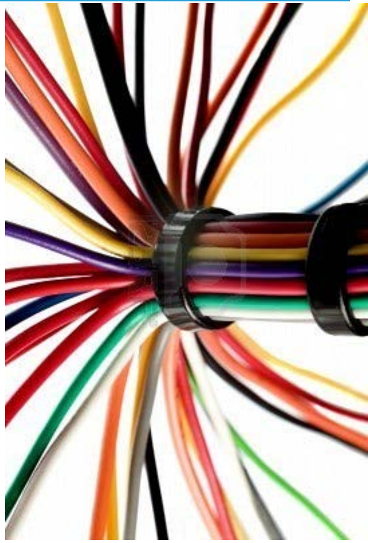


Political Symbol Colors

- parties
- revolutions / movements
- flags

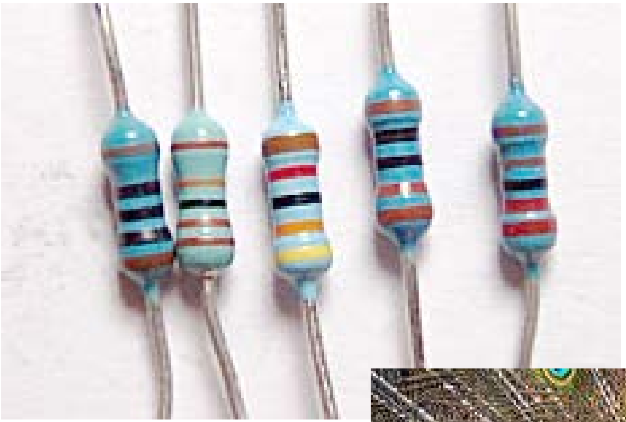
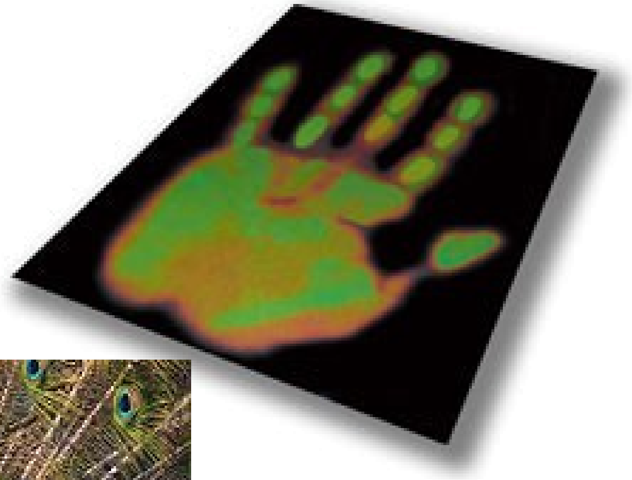
- at home
  - water pipes
  - electrical wires
  - waste separation
- traffic
  - traffic signs
  - traffic lights
  - parking concepts
  - public transport
- ...





Color Labeling

- technology
  - resistors
  - thermochrome colors
- nature
  - courtship [Balz]
  - warning colors
  - protective mimicry [Tarnfarben]
- ...


Color Effect: BLUE

- distance
- faithfulness *[Treue]*
- loyality
- desire
- phantasy
- male
- devine
- peace
- cold
- …

Color Effect: RED

- blood
- energy
- love
- female
- rich, noble
- labor movement
- warm
- corrections
- …

Color Effect: GREEN

- profit
- young love
- hope
- prematurity, unripe
- poison
- nature
- neutral
- environment protection
- …

Color Effect: YELLOW

- sun
- optimism
- enlightenment
- jealousy *[Neid]*
- stinginess *[Geiz]*
- warning color
- warm
- …

Color Effect: BLACK

- end, death
- sadness
- negative emotions
- bad luck
- elegance
- emptiness
- cold
- …